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# Electric Motors and Drives

volume 5

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# Electric Motors and Drives Handbook Volume 5

## Published by The Electricity Forum

The Electricity Forum
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Pickering, Ontario L1W 3V4
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# ELECTRIC MOTORS AND DRIVES HANDBOOK VOLUME 5

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ISBN-978-1-897474-13-6
The Electricity Forum
215 - 1885 Clements Road, Pickering, ON L1W 3V4

Printed in Canada

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# ELECTRICAL MOTOR DIAGNOSTICS FOR GENERATORS PART 1 - THE BASICS

ALL-TEST Pro, LLC

## INTRODUCTION

Electrical Motor Diagnostics (EMD) is a term for test methods and instruments designed for rotating and coil-wound machinery electrical and mechanical analysis. These instruments are used for all motor system related analysis from the generator and prime mover, through the transmission and distribution system, to the electric motor and driven load.

These technologies, for the purpose of this paper, will include Motor Circuit Analysis (MCA), a de-energized test method, and Electrical Signature Analysis (ESA), a more advanced method of Motor Current Signature Analysis (MCSA).

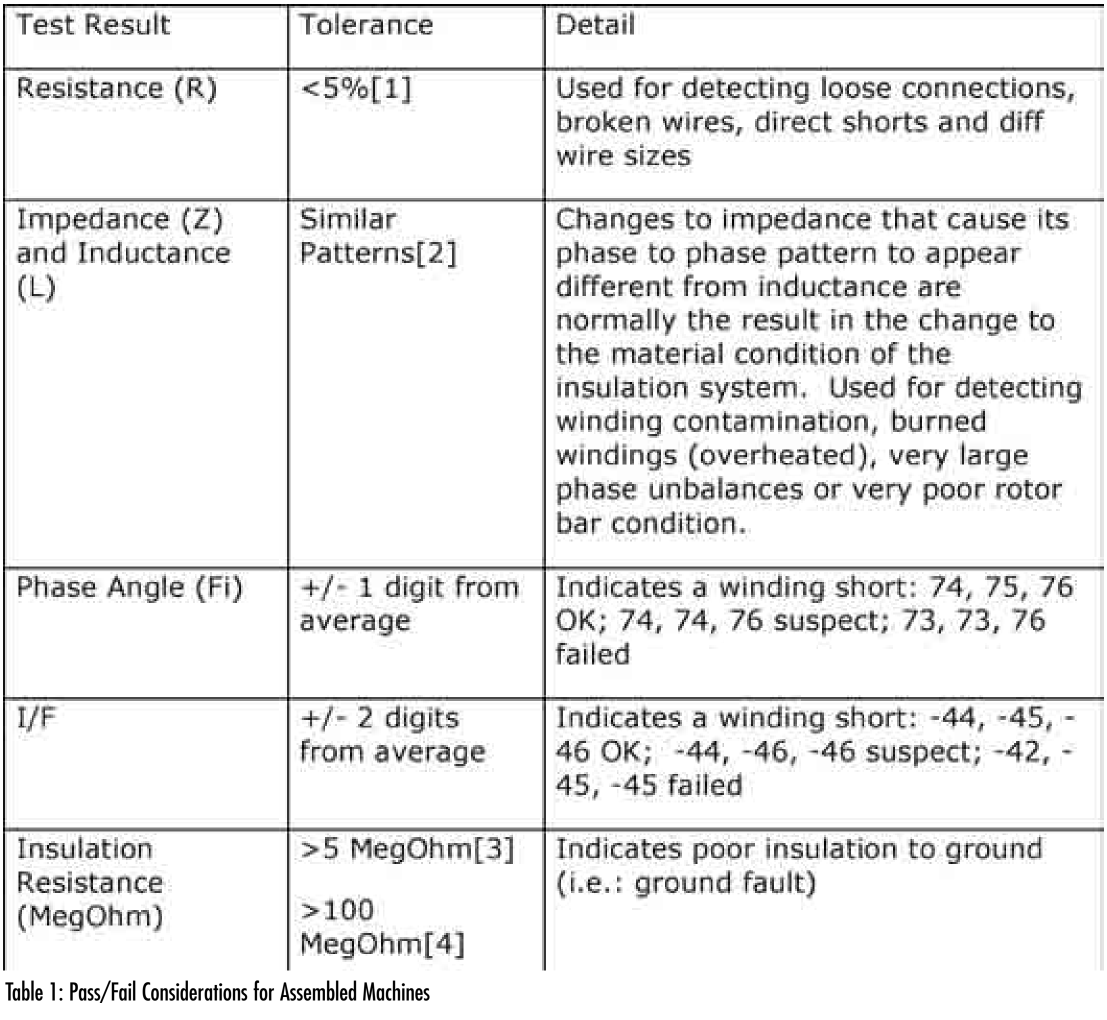
In this paper, we will discuss the concepts behind the testing and analysis of both salient and turbine generators to detect some common generator faults. These faults include bearings, winding shorts in the rotor and stator, insulation to ground faults in the rotor and stator, exciter faults, misalignment and rotating field eccentricity.

## MOTOR CIRCUIT ANALYSIS

MCA is a low-voltage method for testing electric machinery cables, connections, windings and rotor for developing faults. The technique involves individual readings of DC Resistance (R), Impedance (Z), Inductance (L), Phase Angle (Fi), Current/Frequency Response (I/F) and insulation to ground (MegOhm) testing. Resistance is used for detecting loose connections and broken conductors, insulation to ground is used for detecting ground faults, Z and L are matched to evaluate the insulation condition for winding contamination, and, Fi and I/F are used to detect winding shorts. One of the key aspects of MCA is the ability to detect early winding defects that can be trended over time and a time to failure can be estimated.

As a vast majority of the rotating machinery, that MCA is used to evaluate, requires balanced phases, pass fail criteria for individual readings can be developed for both assembled and disassembled machines (Reference Tables 1 and 2). These values indicate a guideline and values outside of these guides normally identify component failures that have occurred, or are developing.

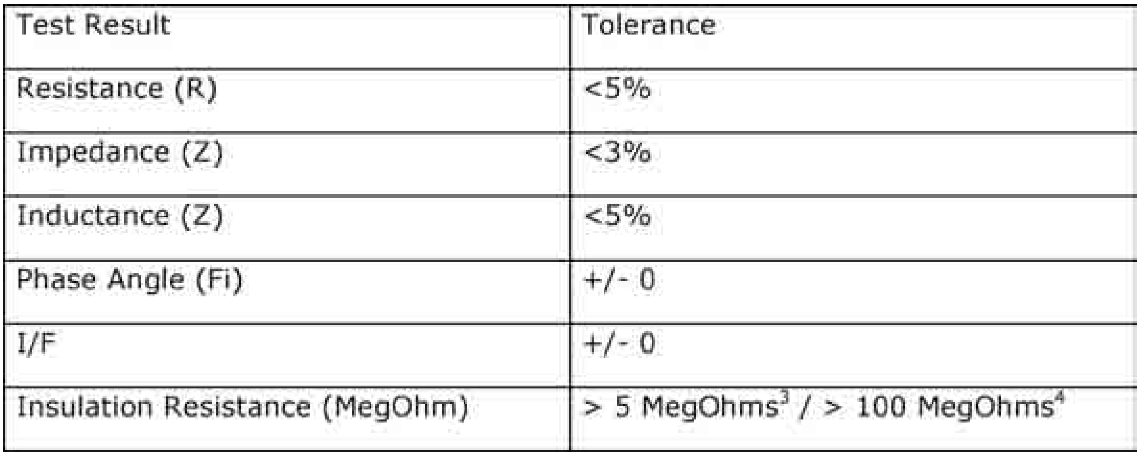
In addition to the power of detecting a motor system defect, the values are trend able without the requirement of temperature adjustments for a majority of faults. This allows for the ability to evaluate condition and provide estimates for time to failure by monitoring changes to the phase to phase unbalances over time.



| Test Result | Tolerance | Detail |
|---|---|---|
| Resistance (R) | <5%[1] | Used for detecting loose connections, broken wires, direct shorts and diff wire sizes |
| Impedance (Z) and Inductance (L) | Similar Patterns[2] | Changes to impedance that cause its phase to phase pattern to appear different from inductance are normally the result in the change to the material condition of the insulation system. Used for detecting winding contamination, burned windings (overheated), very large phase unbalances or very poor rotor bar condition. |
| Phase Angle (Fi) | +/- 1 digit from average | Indicates a winding short: 74, 75, 76 OK; 74, 74, 76 suspect; 73, 73, 76 failed |
| I/F | +/- 2 digits from average | Indicates a winding short: -44, -45, -46 OK; -44, -46, -46 suspect; -42, -45, -45 failed |
| Insulation Resistance (MegOhm) | >5 MegOhm[3]<br>>100 MegOhm[4] | Indicates poor insulation to ground (i.e.: ground fault) |

Table 1: Pass/Fail Considerations for Assembled Machines

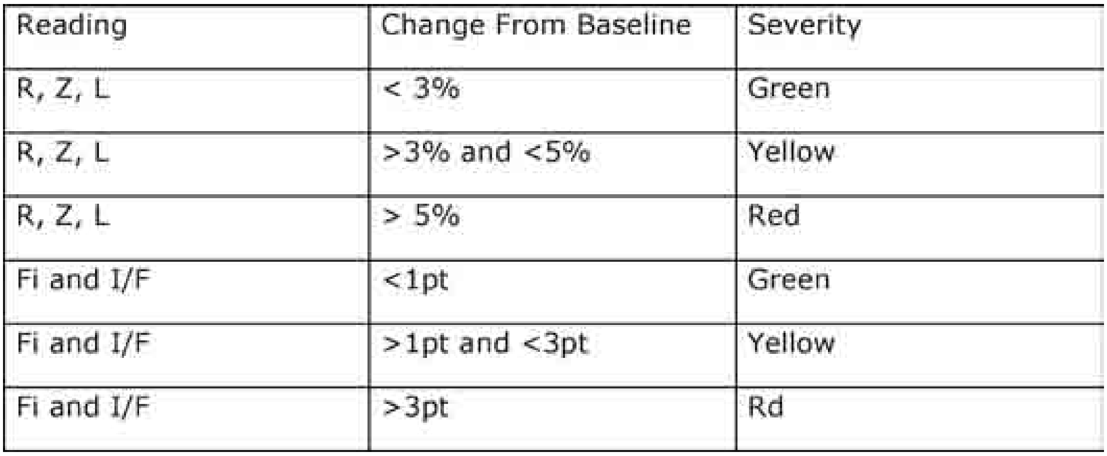
When a motor does not have a rotor in place, such as in a motor repair shop with a stator only, the tolerances change:



| Test Result | Tolerance |
|---|---|
| Resistance (R) | <5% |
| Impedance (Z) | <3% |
| Inductance (Z) | <5% |
| Phase Angle (Fi) | +/- 0 |
| I/F | +/- 0 |
| Insulation Resistance (MegOhm) | > 5 MegOhms[3] / > 100 MegOhms[4] |

Table 1: Pass/Fail Considerations for Assembled Machines

For trending and analysis purposes, MCA is a comparative tool using percent unbalance and difference between tests methods. In the percent unbalance method, the difference between like coils (i.e. between phases in a three phase motor) is trended over time. This method is best for resistance, impedance and inductance. While resistance values are impacted by temperature, for instance, the relative difference between phases is not. By using the percent unbalance method, the user or software do not have to rely upon performing temperature correction calculations. Impedance and inductance are not significantly impacted by temperature. Therefore, the unbalance method is the most convenient way of detecting faults over time. The difference between test methods is used for phase angle and I/F in which the lowest value for each is subtracted from the highest value for each.



| Reading | Change From Baseline | Severity |
|---|---|---|
| R, Z, L | < 3% | Green |
| R, Z, L | >3% and <5% | Yellow |
| R, Z, L | > 5% | Red |
| Fi and I/F | <1pt | Green |
| Fi and I/F | >1pt and <3pt | Yellow |
| Fi and I/F | >3pt | Rd |

Table 3: Reading Change Table for AC Rotating Equipment

## ELECTRICAL SIGNATURE ANALYSIS

Motor Current Signature Analysis (MCSA) refers to the evaluation of current waveforms only, including the demodulation of the current waveform and FFT analysis. Electrical Signature Analysis (ESA) is the term used for the evaluation of the voltage and current waveforms. This provides an increased advantage to diagnostics as power-related, motor-related and load-related signals can be quickly compared. A key consideration when using ESA is that voltage signatures relate to the upstream of the circuit being tested (towards power generation) and current signatures relate to the downstream of the circuit being tested (towards the motor and load).

ESA uses the machine being tested as a transducer, allowing the user to evaluate the electrical and mechanical condition from the control or switchgear. For accurate analysis, ESA systems rely upon FFT analysis, much the same as vibration analysis.

### WHERE RS = RUNNING SPEED

The pass/fail values of the signatures identified in Table 5 are presently based upon the experience of the user. In the case of motor (downstream) analysis, these values relate to current and for generator (upstream) analysis, these values relate to voltage.

The Fast Fourier Transform (FFT) of both current and voltage signatures are normally calculated in dB instead of linear scale. Analysis of the differences in peaks is determined by comparing the dB value measured down from either the peak current or peak voltage value.

### THE COMBINED USE OF MCA AND ESA

MCA requires that the equipment is de-energized while ESA requires that the equipment is energized. These differences offer the user specific analysis strengths for each technology that support each other.

In the case of MCA, it has specific strengths in the areas of:

### CONTROL AND OTHER CONNECTIONS

Cable insulation system health to ground and between phases

Stator winding health to ground and between phases and conductors

Air gap issues between the stator and rotating assembly

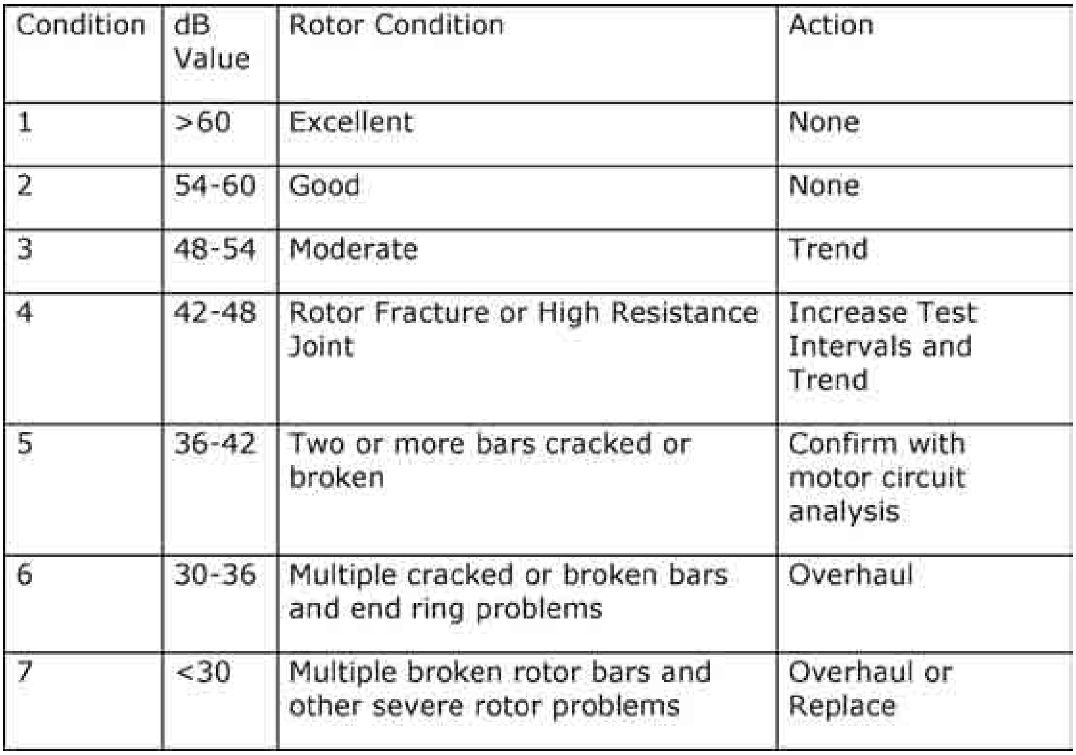
Rotor winding health: wound, induction or synchronous

This includes the ability to provide early failure detection of insulation degradation.

ESA has specific strengths in the areas of:

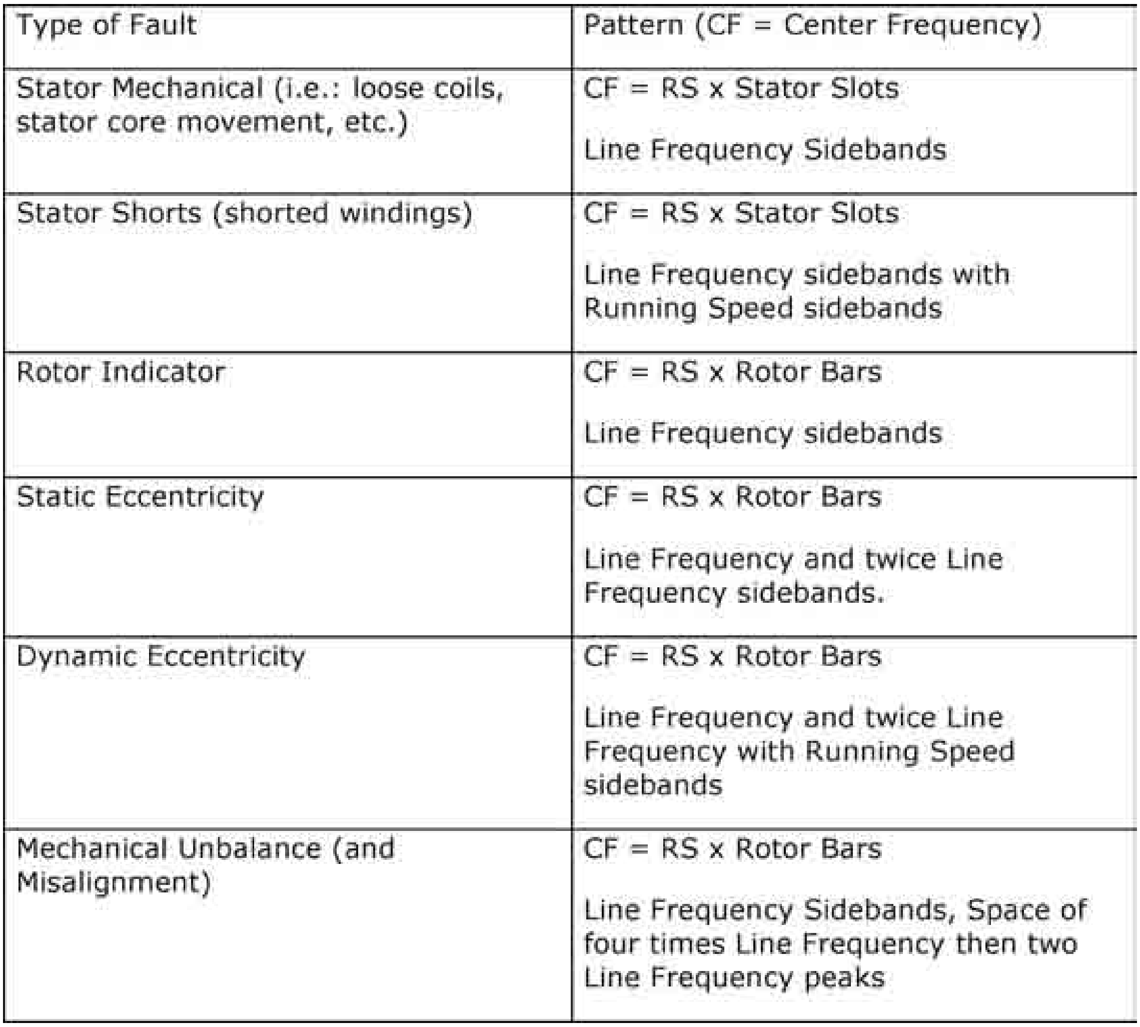
Power quality

Severe insulation breakdown



| Condition | dB Value | Rotor Condition | Action |
|---|---|---|---|
| 1 | >60 | Excellent | None |
| 2 | 54-60 | Good | None |
| 3 | 48-54 | Moderate | Trend |
| 4 | 42-48 | Rotor Fracture or High Resistance Joint | Increase Test Intervals and Trend |
| 5 | 36-42 | Two or more bars cracked or broken | Confirm with motor circuit analysis |
| 6 | 30-36 | Multiple cracked or broken bars and end ring problems | Overhaul |
| 7 | <30 | Multiple broken rotor bars and other severe rotor problems | Overhaul or Replace |

Table 4: Rotor Analysis



| Type of Fault | Pattern (CF = Center Frequency) |
|---|---|
| Stator Mechanical (i.e.: loose coils, stator core movement, etc.) | CF = RS x Stator Slots<br>Line Frequency Sidebands |
| Stator Shorts (shorted windings) | CF = RS x Stator Slots<br>Line Frequency sidebands with Running Speed sidebands |
| Rotor Indicator | CF = RS x Rotor Bars<br>Line Frequency sidebands |
| Static Eccentricity | CF = RS x Rotor Bars<br>Line Frequency and twice Line Frequency sidebands. |
| Dynamic Eccentricity | CF = RS x Rotor Bars<br>Line Frequency and twice Line Frequency with Running Speed sidebands |
| Mechanical Unbalance (and Misalignment) | CF = RS x Rotor Bars<br>Line Frequency Sidebands, Space of four times Line Frequency then two Line Frequency peaks |

Table 5: Signature Multipliers

Loose or open coils or stator

Loose or open rotor or rotor coils

Loose connections

Air gap problems, including static and dynamic eccentricity

Bearings and mechanical condition, including alignment

Attached mechanical systems

When used in combination, the technologies provide some overlapping capabilities, but specifically they provide a complete overview of the system being evaluated, with a high degree of accuracy.

## BASIC GENERATORS

There are two basic types of generator systems. These include turbo-synchronous machines and salient-pole synchronous machines. There are a large variety and variation of each type, so we will cover the basic assembly of both in this paper.

The turbo-synchronous machine is most commonly used in high-speed generators (two and four pole) used for high-voltage power generation. The general assembly resembles a three-phase induction motor with the following specifics:

The stator (armature) resembles a three-phase motor winding. The DC fields of the turbine rotor cut through the conductors and generate power which is supplied to the distribution system from this component.

The turbine rotor (fields) resembles the squirrel-cage rotor of an induction machine. This component carries the DC power from the exciter and is driven by a prime mover such as a jet engine or steam turbine. It tends to be long and narrow for horizontal machines.

The exciter can be separate from the machine, in which brushes supply power to the rotor, or brushless, in which a small DC generator is mounted directly to the turbine rotor shaft. The exciter provides DC power to the turbine rotor.

The salient-pole machine is one of the more common smaller, low voltage, low-speed (1800 RPM or less, 4-pole) generation systems. The distinction is that the rotor contains a series of individual wound-coils which also contain an amortissieur winding, in most cases.

The stator (armature) resembles a three phase motor winding. The DC fields of the salient-pole rotor cut through the conductors and generate power which is supplied to the distribution system from this component.

The salient rotor (fields) incorporate an even number of pole pieces that radiate out from the rotor shaft. These poles carry the DC current that generates the rotating DC fields.

The exciter can be separate from the machine, in which brushes supply power to the rotor, or brushless, in which a small DC generator is mounted directly to the rotor shaft. The exciter provides DC power to the rotor.

Both machines can be evaluated in the same way that you would evaluate electric motors of similar design. In the case of ESA, you would evaluate the signatures using voltage spectra versus current spectra.

## CONCLUSION

Energized testing of generators requires the ability to view the voltage signature of the generator and this requires equipment that can perform Electrical Signature Analysis, not just Motor Current Signature Analysis. The purpose of this paper has been to provide a review of MCA and ESA, as well as a discussion of the construction of turbine and salient generators. The general analysis of generators is performed in a similar manner of any other AC machine.

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# ELECTRICAL MOTOR DIAGNOSTICS FOR GENERATORS PART 2 - CASE STUDIES

Howard W. Penrose Ph. D, ALL-TEST Pro, LLC

## INTRODUCTION

In Part 1 of this 2 Part series, the basic principles of Motor Circuit Analysis (MCA) and Electrical Signature Analysis (ESA), and how they relate to turbine and salient-pole generators was discussed. In Part 2, we shall discuss case studies related to marine generators and wind turbine generators. These cases shall discuss both generators in poor condition and in good condition. Following Part 2, Part 3 shall discuss the details of how these analysis were performed, including how condemning criteria was formulated.

## CASE #1: MARINE SALIENT-POLE GENERATOR, INSULATION FAILURE

A marine generator on board a military vessel was experiencing increasing over-air-temperature faults during operation. These occurred within 24 hours of operation and gradually worked towards occurring every 6 hours of operation during the course of eight months. The engine and cooling temperatures were evaluated and found to be operating satisfactorily.

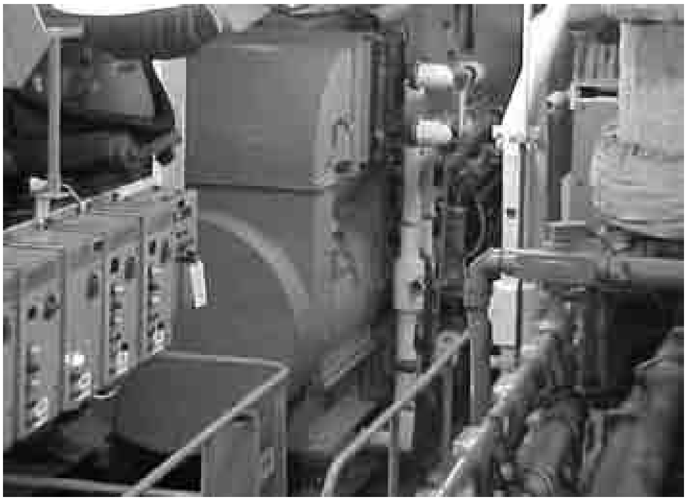


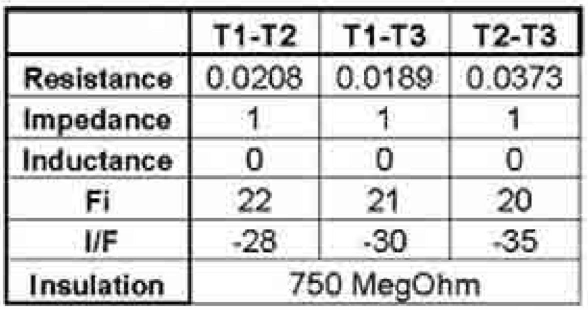
Figure 1: Generator

The generator had been installed on the vessel following eighteen years of storage in an uncontrolled environment. It was determined that Electrical Motor Diagnostics (EMD) would be used to evaluate the condition of the system.

Testing was performed at the switchgear using MCA. The first set of data identified a problem in the circuit (Table 1). A second set of tests were performed in the connection box at the generator (Table 2) which identified both a winding short and poor insulation condition (unmatched Z and L).

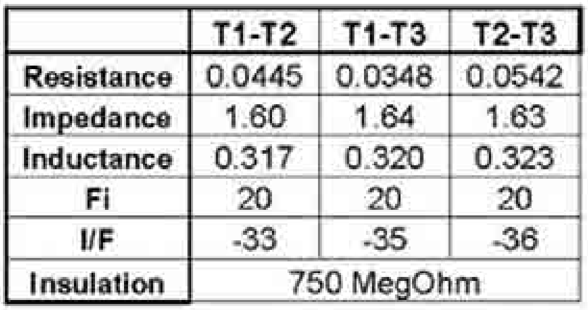
Figure 2: Switchgear Test Points

Table 1: MCA Test at Switchgear



| | T1-T2 | T1-T3 | T2-T3 |
|---|---|---|---|
| Resistance | 0.0208 | 0.0189 | 0.0373 |
| Impedance | 1 | 1 | 1 |
| Inductance | 0 | 0 | 0 |
| Fi | 22 | 21 | 20 |
| I/F | -28 | -30 | -35 |
| Insulation | 750 MegOhm | | |

Table 2: MCA at Generator



| | T1-T2 | T1-T3 | T2-T3 |
|---|---|---|---|
| Resistance | 0.0445 | 0.0348 | 0.0542 |
| Impedance | 1.60 | 1.64 | 1.63 |
| Inductance | 0.317 | 0.320 | 0.323 |
| Fi | 20 | 20 | 20 |
| I/F | -33 | -35 | -36 |
| Insulation | 750 MegOhm | | |

As it requires removal of the generator through a hole in the hull of the ship, additional testing was performed using ESA over a period of 30 minutes.

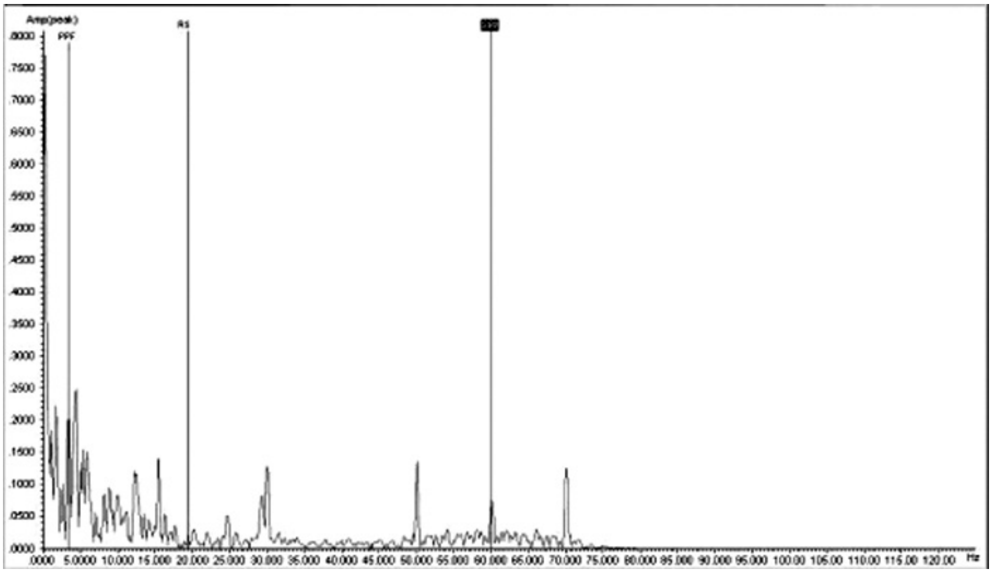


Figure 3: ESA at ‘0’ Minutes

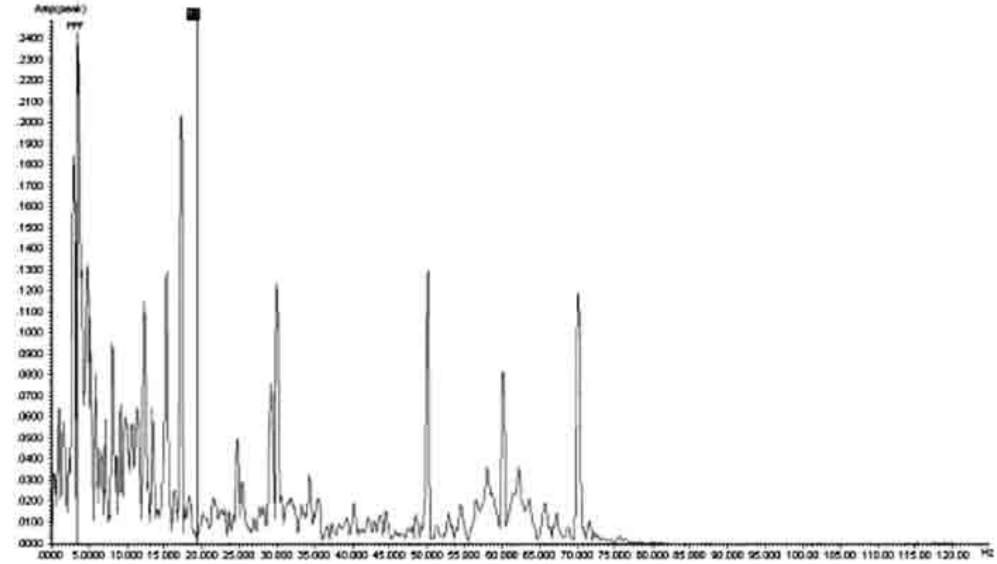


Figure 4: ESA at ‘10’ Minutes

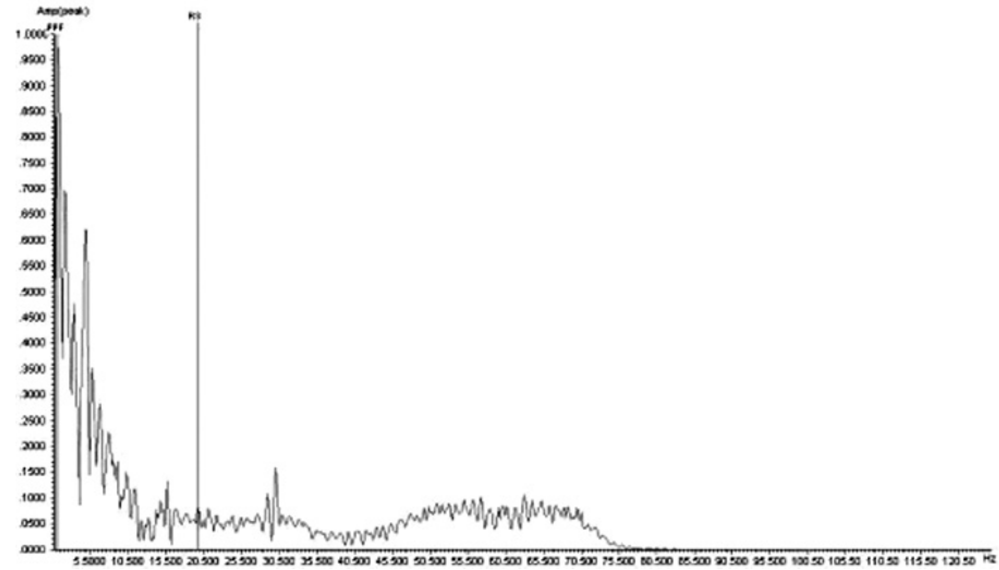


Figure 5: ESA at ‘20’ Minutes

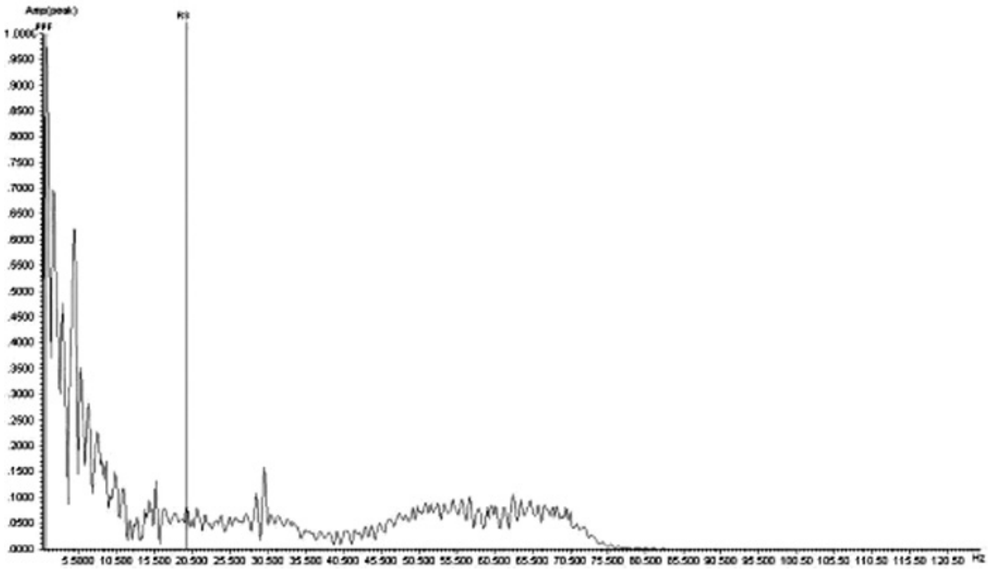


Figure 6: ESA at '30' Minutes

At the end of the ESA test period, another set of MCA data was performed while the generator was warm (Table 3).

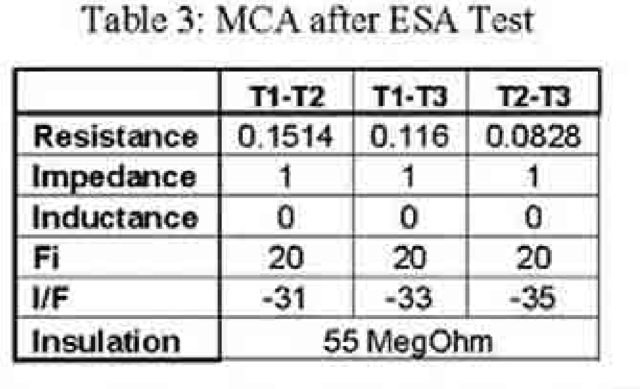


Table 3: MCA after ESA Test

| | T1-T2 | T1-T3 | T2-T3 |
|---|---|---|---|
| Resistance | 0.1514 | 0.116 | 0.0828 |
| Impedance | 1 | 1 | 1 |
| Inductance | 0 | 0 | 0 |
| Fi | 20 | 20 | 20 |
| I/F | -31 | -33 | -35 |
| Insulation | 55 MegOhm | | |

The reduction in insulation resistance from 750 MegOhm to 55 MegOhm indicates a temperature rise somewhere in the insulation system of approximately 140 C.

The vessel was scheduled for work in three months following these tests, in which the time included a cruise overseas. The question was whether the generator would be serviceable during this time. If not, the vessel would be unable to perform its mission.

A review of loads and temperatures was performed along with the data from the EMD analysis. Based upon historical references and estimated time to failure research, it was determined that the generator could be operated in parallel with a second generator at 50% load, or less. Watch standers were given instructions to observe for variations in current unbalance as an indicator of advanced winding failure. Recommendations were provided to the vessel's shore engineering support group for the storage of rotating machines and generators.

After its mission, the generator was removed for repair (Figure 7) and shipped to the contracted repair shop.

Repair requirements included complete rewind of the stator and rotor with approved overtime in order to meet the vessel's shipyard schedule. Acceptance inspections were performed at the repair center's site under load.

Figure 7: Generator Removal

Several details on the repair were determined during the inspection:

1. The lead wire was reduced in size. This increase the heat related losses at the leads and restricted the maximum current capability of the generator.

2. The winding conductors were increased in size. While this allowed the generator to operate slightly cooler, it affected the circuit enough that significant tuning was required to be able to synchronize the generator.

3. The rotating fields were not rewound as was determined by the ESA analysis. This resulted in a reduced reliability in the life of the generator.

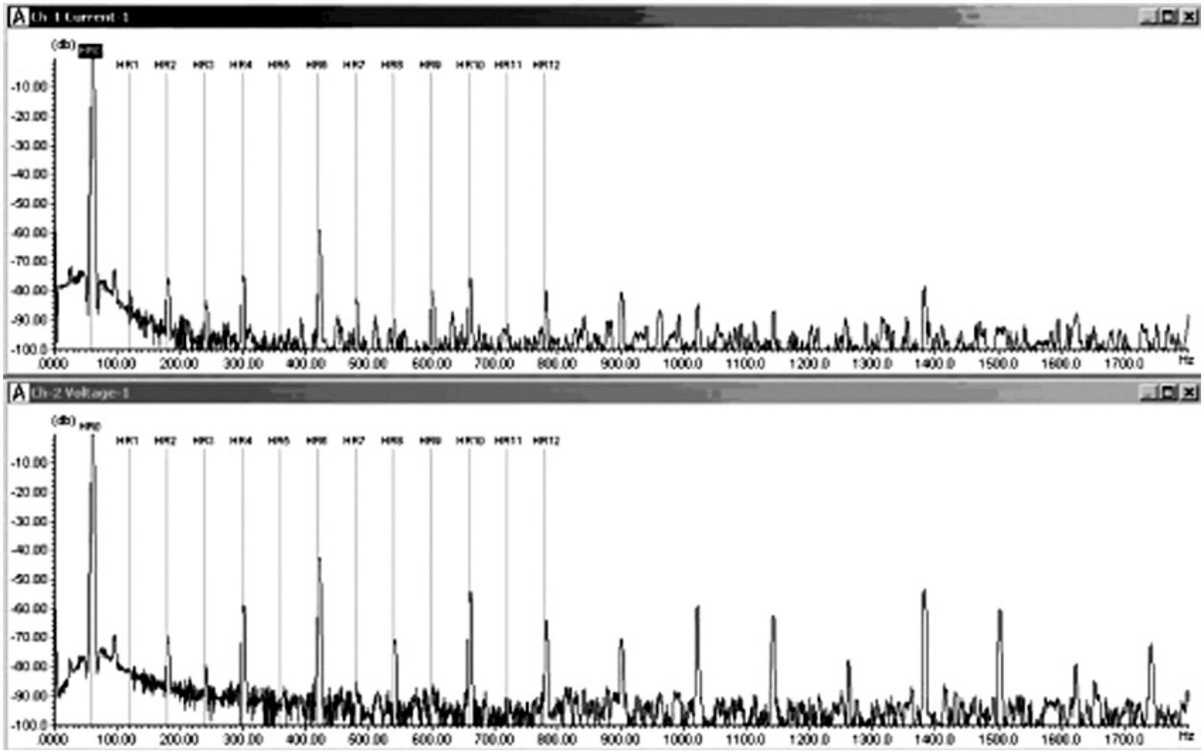


Figure 8: Acceptance ESA Test

## CASE #2: MARINE SALIENT-POLE GENERATOR, POOR CONDITION

In this generator, both MCA and ESA were performed as part of a routine maintenance.

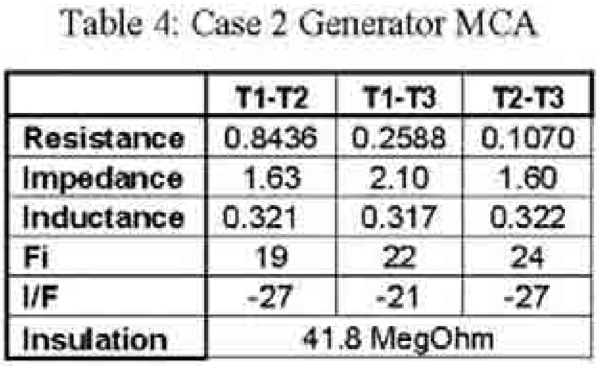


Table 4: Case 2 Generator MCA

| | T1-T2 | T1-T3 | T2-T3 |
|---|---|---|---|
| Resistance | 0.8436 | 0.2588 | 0.1070 |
| Impedance | 1.63 | 2.10 | 1.60 |
| Inductance | 0.321 | 0.317 | 0.322 |
| Fi | 19 | 22 | 24 |
| I/F | -27 | -21 | -27 |
| Insulation | 41.8 MegOhm | | |

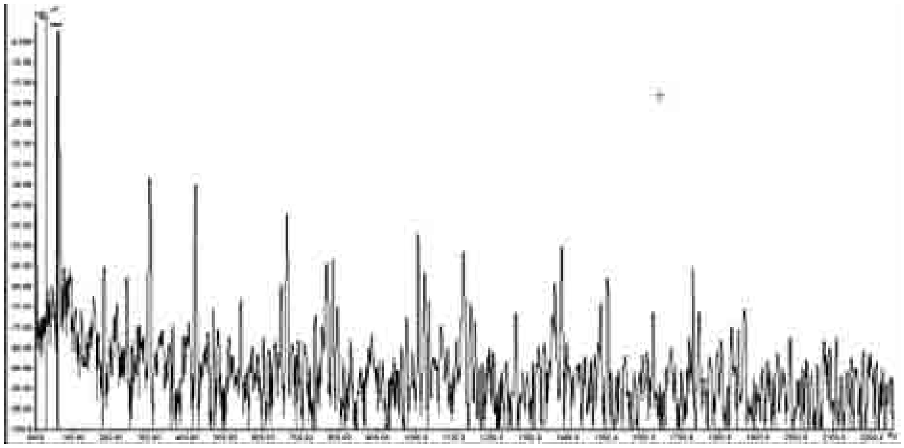


Figure 9: Case 2 Generator Voltage Signature

The MCA analysis involved positioning the rotor to a set location and performing an analysis. A loose connection, low insulation to ground, impedance and inductance matching and questionable winding conditions were determined. However, as will be discussed in Part 3, the Fi and I/F primarily are used as trendable values unless specific procedures are followed.

The signature found in Figure 9 indicates a relatively good rotor with the line frequency sidebands of the number of rotor fields times the line frequency (in this case, 360 Hz +/- 60Hz) with a gradually dampening set of harmonics.

Based upon these findings, coupled with a visual inspection, the generator should be scheduled for a cleaning. It is expected that the winding conditions (L and Z) will balance out and the insulation resistance will improve.

## CASE #3: WIND TURBINE GENERATORS, GOOD

A common issue with wind turbine generators is the passage of grit or dust through the generator windings causing

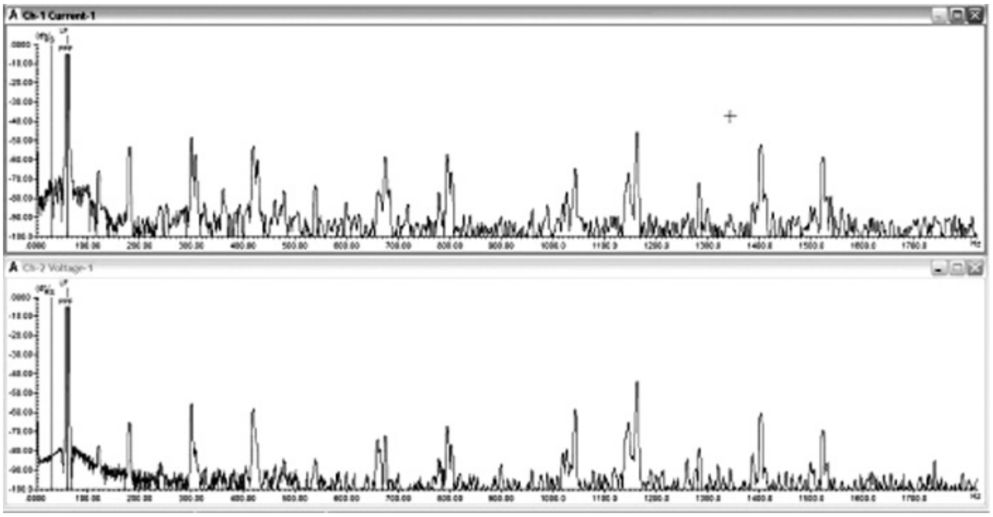


Figure 10: Good Readings

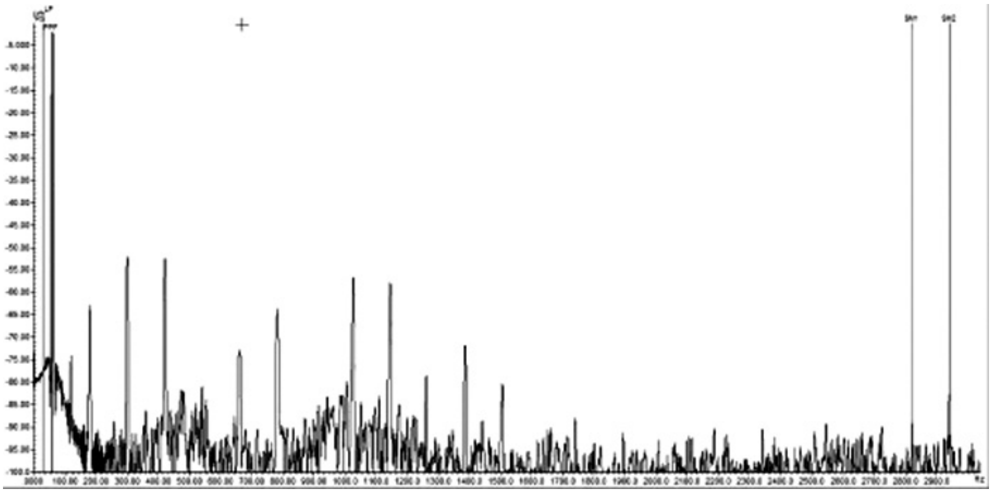


Figure 11: Loose Coils

winding shorts, bearing problems, etc.

In figure 10, the peaks are dominant in current (upper spectra) which is related to the load. The voltage signatures identify a relatively low level of rotor frequency. This identifies a good online analysis of this system.

## CASE #4: WIND TURBINE GENERATORS, LOOSE COILS

During a routine analysis, a signature was determined as 60Hz sidebands around the running speed times the number of stator slots of the generator. As identified in Part 1 of this series, this indicates 'Stator Mechanical' which is defined as loose coils or a loose stator. In this case, it was determined to be, most likely, loose coils.

## CONCLUSION

The electrical motor diagnostics techniques of motor circuit analysis and electrical signature analysis are uniquely adapted for troubleshooting and trending of developing generator electrical and mechanical problems. Used together, they can also be used to detect potential warranty issues in new and repaired machines prior to bringing the generators online.

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# PLANT EFFICIENCIES BENEFIT BY SELECTION OF SYNCHRONOUS MOTOR

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Richard C. Schaefer, Basler Electric, Highland, IL

## ABSTRACT

Induction motors are often the choice for various industrial production processes. Use of an induction motor, however, will result in increased lagging power factor burdens in the plant. This burden often must be corrected by adding capacitors. If not, the result is the penalty of larger kVA burdens to the interconnected system. For low speed applications, synchronous motors may be a better choice when equipped with accessories that offer power factor control. The synchronous machine, with the aid of an intelligent excitation controller, can control power factor to reduce the plant reactive loading to the connected system.

This paper will discuss the application of the synchronous motor at the Lion Oil Refinery and the digital excitation system used to control the machine power factor.

## I. BACKGROUND

Lion Oil is a refinery in El Dorado, Arkansas, that processes petroleum products. Environmental mandates that go into effect June 2006 include new clean air regulations requiring a reduction in sulfur emissions for diesel fuel from 500 parts to 15 parts per million.

Current refining equipment is not designed to process the petroleum product at the increased pressures and higher temperatures needed to meet the EPA regulations. To meet the refining requirements, a new higher-rated motor connected to a hydrogen-reciprocating compressor would be needed to drive the refining process.

Lion Oil currently utilizes induction motors, ranging in size from 100 to 3500 horsepower. With such a large number of induction motors, power factor is an issue at the plant. Capacitors are used for correction to minimize penalties from the electric utility. The decision to use a synchronous motor instead of an induction motor was based upon the need to have an optimally efficient plant with low operating cost.

Figure 1: Picture of Lion Oil Motor

## II. DECISION FOR SELECTION OF SYNCHRONOUS MOTOR

The induction motor has fixed stator windings that are electrically connected to the AC power source. Current is induced in the rotor circuit via transformer action, resulting in a magnetic field that interacts with the stator field causing rotation.

The rotor must rotate slower than the stator field for the induction to occur, thus an induction motor operates at less than synchronous speed using no other power source to excite the rotor's field.

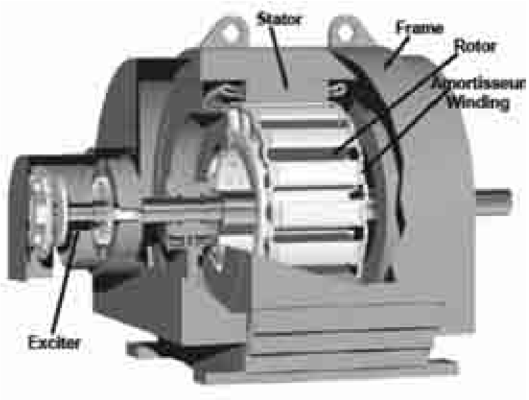

Figure 2: Synchronous Motor

Motors, especially those operating at 600 RPM and below, have lower operating efficiency and, inherently, a lagging power factor that draws exciting current from the connected source. Since an induction machine draws all exciting current from the AC source, it may take in the range of 0.3 to .6 p.u. reactive magnetizing kVA per HP of operating load.

The synchronous motor has fixed stator windings electrically connected to the AC supply with a separate source of excitation connected to a field winding on the rotating shaft. Magnetic flux links the rotor and stator windings causing the motor to operate at synchronous speed. See Figure 2.

While induction motors can be started and accelerated to steady state running condition simply by applying AC power to the fixed stator windings of the motor, a synchronous motor starts as an induction motor. Then, when rotor speed is near synchronous speed, the rotor is locked in step with the stator by application of DC voltage and current applied to the rotor of the motor.

Once the synchronous motor is operating at synchronous speed, it is possible to alter the power factor of the motor by varying the excitation supplied to the motor's field. Since power factor correction could be provided, a synchronous motor was chosen.

This paper will describe the characteristics of the synchronous motor, field application and the excitation system selected for this application. For Lion Oil, the new synchronous motor would be rated for 5000 HP, 13,800 Vac, operating at 327 RPM.

## III. CONSTRUCTION OF A SYNCHRONOUS MOTOR

Synchronous motors consist of a fixed stator and a field that rotates concentric with the stator. The stator contains armature windings that are electrically connected to the AC supply system while the rotor contains a field winding that is electrically connected to a source of excitation (dc). See Figure 3.

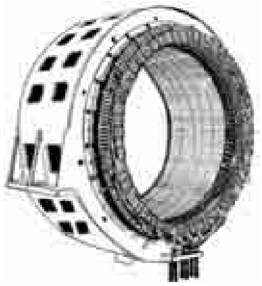

Figure 3: Stator Winding

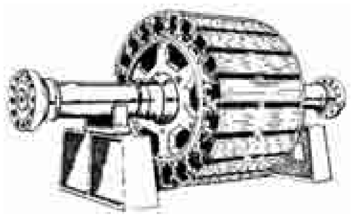

Figure 4: A Rotor for a Synchronous Motor

Since the primary purpose of the field winding is to create a rotating magnetic field, the field winding is wound around poles attached to the rotor in a configuration that produces magnetic north and south poles that are 180 electrical degrees apart. See Figure 4

During starting of the motor, the field winding is not effectively coupled with the armature windings in the stator and no net torque is produced in the field when AC power is connected to the stator winding.

To produce starting torque, a supplementary winding is provided on the rotor that effectively couples electromagnetically with the armature windings. This winding is a squirrel cage arrangement of bars placed across each poleface that are electrically shorted at each end. The squirrel cage winding on the rotor is formally known as the damper or amortisseur winding.

When AC power is connected to the stator, current is induced in the squirrel cage winding.

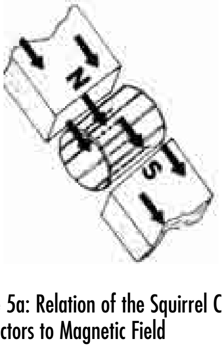

Figure 5a: Relation of the Squirrel Cage Conductors to Magnetic Field

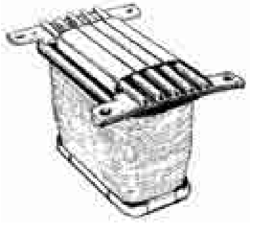

Figure 5b: A Rotor Field Pole with Squirrel Cage

This results in a net torque that is applied to the rotor, as shown in Figures 5a and b.

This squirrel cage winding is also used in the induction motor to produce motor torque during starting and running operation. Torque is produced by the electromagnetic interaction of stator and rotor only when a slip speed exists. Thus, the induction motor speed increases from zero until just below synchronous speed as torque decreases with increasing rotor speed.

As noted, the synchronous motor is started like an induction motor with the torque on the rotor dependent on the difference between the rotor speed and the frequency of the power being applied to the stator winding. The torque supplied by the squirrel cage is at a maximum when AC power is first supplied to the stator winding and decreases as the rotor accelerates, until it reaches zero torque when the rotor approaches synchronous speed. The absolute value of the accelerating torque is a function of the resistance of the bars in the squirrel cage. Higher resistance bars produce higher starting torque (and hotter squirrel cage winding), while lower resistance bars produce lower starting torque with less heat generation.

If the starting torque produced by the squirrel cage winding is not adequate to roll the rotor, the rotor is said to be locked and AC power must be quickly removed from the stator windings to avoid overheating both the armature and the squirrel cage windings. As shown in Figure 6, the stator winding is connected to the AC supply system at startup, and the bars of the squirrel cage winding on the rotor produces an accelerating torque on the rotor. The field winding is connected to a field discharge resistor during startup, while no external excitation is applied to the field See Figure 6.

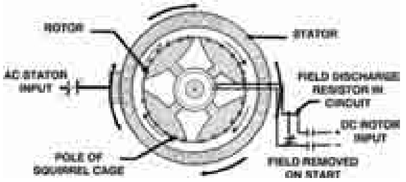

Figure 6 (up): During Start, the Rotor Poles will Rotate at a Slower Speed than the Stator Frequency, Inducing a Slip.

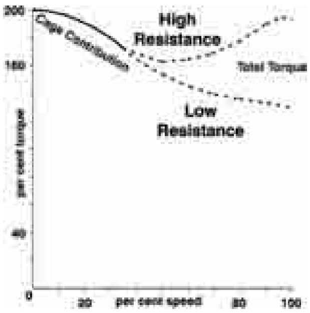

Figure 7 (left): Squirrel Cage at Different Starting Resistance Values

As the rotor accelerates, the field winding is coupled to the stator field via the armature winding. AC current is induced into the field based upon the difference between the frequency of the applied AC voltage to the motor and the frequency associated with the instantaneous speed of the rotor. If the field winding were open circuited during startup, dangerously high voltages could be induced in the field winding, hence a discharge resistor is used to limit the voltage seen by the field winding during startup while dissipating the energy induced in the field. The resistance of the discharge resistor also affects the synchronizing torque available as the rotor approaches rated speed. Synchronizing torque increases with the resistance of the field discharge resistor.

A low resistance produces lower synchronizing torque, as shown in Figure 7.

Insulation limits of the field winding limit the size of the resistor, because induced field voltage increases with increasing values of the discharge resistor. Sizing the discharge resistor is an art that balances starting torque and allowable field voltage during startup.

## IV. STARTING THE SYNCHRONOUS MOTOR

Over the years, several methods have been used to start synchronous motors, the most common approach is starting across the line with full AC voltage to the armature windings.

The squirrel cage windings begin the task of accelerating the motor from zero speed. As the motor speed increases, the discharge resistor provides the torque required for the motor to reach synchronous speed. When the synchronous speed is reached, the discharge resistor is switched out of the field circuit and excitation can be applied to lock the stator and field poles into synchronism. It is important to properly time the application of excitation to the main field. The purpose of the DC excitation system is to apply current to the field winding, creating a rotating electromagnet field that couples the rotor field to the rotating AC field in the armature winding when the motor is operating at synchronous speed. When DC excitation is applied to the motor field, the position of the rotor with respect to the stator magnetic field determines the reaction of the rotor.

If the N and S rotor and stator poles are aligned, such that the magnetic flux lines flow easily from the rotor through the airgap, the rotor flux will lock in step with the stator flux and the motor will become synchronous. If the rotor poles are 180 electrical degrees out of phase with the stator poles, but motor acceleration is decreasing the angle of displacement, it is likely that accelerating torque plus magnetic attraction will combine to draw the rotor rapidly into pole alignment with the stator. Synchronizing additionally depends on the slip frequency between rotor and stator. Synchronizing torque from the magnetic linkage of rotor and stator must be sufficient to accelerate the rotor to keep it locked in step.

The most straightforward approach to synchronous motor starting is to monitor the frequency of the voltage across the field discharge resistor. As the motor nears synchronous speed, the slip frequency approaches zero across the resistor. See Figure 8.

At a specific slip frequency and rotor angle, DC is applied to the main field and the discharge resistor is switched out to provide a very smooth transition from starting to synchronous operation. Modern application of the field for synchronous motors utilizes solid state devices that control the removal of the discharge resistor and apply the excitation at the proper time in lieu of the breakers or contactors that have been used historically in the past.

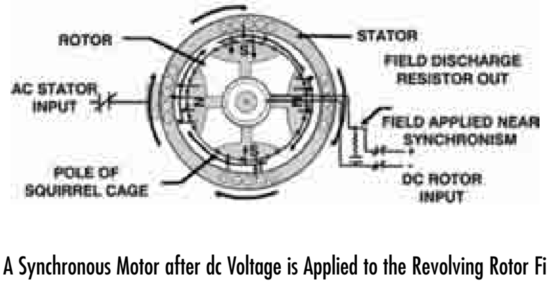

Figure 8: A Synchronous Motor after dc Voltage is Applied to the Revolving Rotor Field and the Field is in Step with the Stator Frequency

## V. SYNCHRONOUS OPERATION

To understand normal operation of the motor, it is important to understand why the field rotates at synchronous speed. Each set of field poles is matched with an equivalent set of stator poles. Since like poles, for example north and north, repel and unlike poles attract, the poles of the rotating field tend to align themselves with opposite poles produced in the stator by the AC power applied to the armature windings of the motor, as shown in Figure 9.

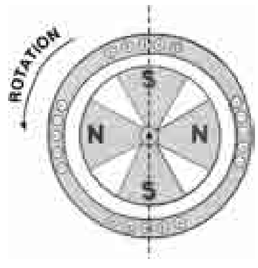

Figure 9: Opposite Polarity Poles are Matched

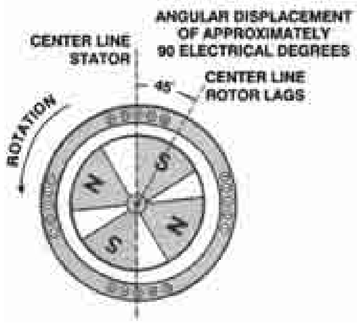

Figure 10: Center Lines of Opposite Polarity Poles with Angular Displacement Approaching 45°

When this condition is achieved, the motor is said to be in step. When the motor is lightly loaded, the centerline of the rotor poles will nearly align across the air gap between the pole face and the stator with the center line of an opposite polarity stator pole.

As the motor is loaded, the angular displacement of the center lines will increase. As the angular displacement approaches approximately 45 mechanical degrees (90 electrical degrees) as shown in Figure 10, the motor is approaching pull-out torque. Beyond this point, the rotor poles will no longer be in step with the stator poles, and the rotor poles will slip, producing a sudden increase in current draw from the AC system.

Once the synchronous motor's field poles are in step with the stator frequency, two factors determine the synchronous speed of the motor. The first is the frequency of the applied voltage; the second is the number of poles in the motor.

$$\text{Speed} = \frac{\text{Freq} \times 120}{\text{Poles}}$$

## VI. BENEFITS OF THE BRUSHLESS EXCITED SYNCHRONOUS MOTOR

The brushless excited synchronous motor is the most common type exciter supplied today for use with synchronous motors, requiring no brushes or collector ring maintenance. The exciter is physically direct connected to the motor shaft. The brushless exciter has a three -phase AC armature winding. See Figure 11. The stationary field winding is on poles on the stator and is connected to an excitation supply source. The generated AC current is directly connected along the shaft to a rotating three-phase diode wheel, where the AC is rectified to DC before

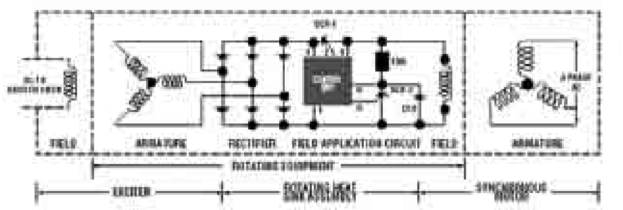

Figure 11: Field Application Circuit Drawing

going to the motor's main field. The magnitude of the motor field current is adjusted by changing the current to the stationary exciter field by a DC source.

## VII. SOLID STATE FIELD APPLICATION SYSTEMS

The efficiencies of solid state field application control has provided an economical and reliable means of applying excitation to the motor's field at the precise moment that insures optimum synchronization. See Figure 12

The function of the Field Application System provides three important elements:

- Provide a discharge path for the current induced in the field of the motor during starting, and open this circuit when excitation is applied.
- Apply field excitation positively when the motor reaches an adequate speed. The excitation should be applied with such polarity that maximum torque will be obtained at the time of pull-in.
- Remove excitation and reapply the field discharge resistor immediately if the motor pulls out of step.

Referring to Figure 11, the field discharge resistor protects the motor field winding from the high voltage induced during starting and provides the voltage source for the control circuit. The AC output of the exciter is converted to dc by the rotating rectifier diodes. This output is switched on or off to the motor field winding by a silicon controlled rectifier SCR-1, which is gated by the control circuit.

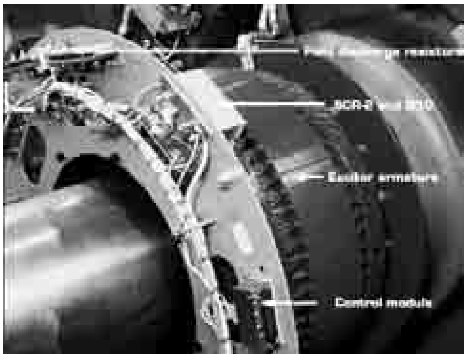

Figure 12: Brushless Exciter

The solid state field application system shown in Figure 11 has a control circuit that keeps the SCR-1 from firing until the induced field current frequency is very low, representing a close approach to synchronous speed, and then fires the rectifier SCR-1 at the proper time and applies excitation to the synchronous motor field. At the same time, the field discharge resistor is removed from the circuit. This is done by the inherent operating characteristics of silicon controlled rectifier, SCR-2. This frequency sensitive part of the control circuit ensures that field excitation is applied at the proper pull-in speed for successful synchronizing and at the proper polarity to give maximum pull-in torque with minimum line disturbance.

The control circuit operates to remove excitation should the motor pull out of step due to a voltage step or excessive mechanical load. On the first half cycle after pull-out, the induced field voltage causes the net field current to pass through zero, turning SCR-1 off, automatically removing excitation. SCR-2 operates to connect the field discharge resistor back in to the circuit. During this time, the motor operates as an induction motor.

When conditions permit, field is then re-applied as during starting. In Figure 11, the voltage from the exciter rectifier is blocked by SCR-1 until the point of synchronization. The field has an alternating voltage causing current to flow first through SCR-2 and the discharge resistor. On the next half cycle, current flows through the diode and discharge resistor. The control circuit waits until the frequency drops to the preset value, indicating the rotor is at an adequate speed. Then, after a North pole on the stator is in the right position to be attracted to what will be a South pole on the rotor, it triggers SCR-1 to apply excitation.

If the rotor does not synchronize, it will slip a pole, the induced field voltage will oppose the exciter voltage causing the current to go to zero, turning SCR-1 off. SCR-2 in Figure 11 turned on only at a voltage higher than the exciter voltage so it will not be on when SCR-1 is on.

## VIII. SYCHRONOUS MOTOR CONTROLS

### POWER FACTOR

Power factor is the factor by which apparent power, or kVA, is multiplied to obtain actual power, or kW, in an AC system. It is the ratio of the in-phase component of current to total current. It also is the cosine of the angle by which the current lags (or leads) the voltage. The conversion of electrical energy to mechanical energy in a motor is accomplished by magnetic fields. The poles rotate around the stator. When voltage is applied to a motor, an armature current flows to provide the necessary magnetic push (mmf or ampere turns) to produce a flux that in turn, produces a voltage (back emf) that opposes the applied voltage. This mmf is a magnetizing current. It is lossless, except for the I2R losses in the winding and any core loss due to the changing flux in the iron. The magnetic energy is transferred from the line to the motor and back again each half cycle. The net power is zero, and the power factor is zero.

The power factor of a synchronous motor is controllable within its design and load limits. It may operate at unity, leading or, in rare cases, lagging power factor.

Once the synchronous motor is synchronized, the field poles on the rotor are in line with the rotating magnetic poles of the stator. If DC is applied to the rotor pole windings, the rotor can supply the necessary ampere turns to generate the flux that produces the internal motor voltage. Thus, the field current can replace part or all of the magnetizing current. In fact, if more DC field current is supplied, the increased flux will try to increase the line voltage. To increase the line voltage, the motor will supply AC magnetizing current to all "magnets" on the system to increase their magnetic flux. This is leading power factor.

The synchronous torque developed is roughly proportional to the angle of lag (load angle) of the motor rotor with respect to the terminal voltage which, at full load, is in the area of 20 to 30 electrical degrees. If a restraining force is applied to the motor shaft, it will momentarily slow down until a torque is developed equal to the applied restraint. The motor will then continue to operate at synchronous speed.

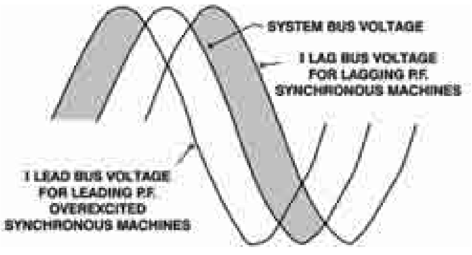
SYSTEM BUS VOLTAGE
I LAG BUS VOLTAGE FOR LAGGING P.F. SYNCHRONOUS MACHINES
I LEAD BUS VOLTAGE FOR LEADING P.F. OVEREXCITED SYNCHRONOUS MACHINES

Figure 13: Leading and Lagging Current as Affected by Field Excitation on the Synchronous Motor

Figure 13 illustrates how the change in the excitation causes the AC line current to either lead the AC source voltage, be in phase with the source voltage or lag the source voltage depending upon if the synchronous motor is over or under excited.

### "V" CURVES

It is generally assumed that the line voltage will be substantially constant, and it is apparent from the preceding discussion that load, excitation, line amperes, and power factor are closely related. This relationship is readily expressed by a family of characteristic curves known from their shape as "V" curves. These are represented in Figure 14 that for each curve the power is constant and the excitation is varied to give different magnetizing currents. The minimum value of line amperes for each load condition is at 1.0 or unity power factor. As excitation is decreased, the line current will increase and the motor will operate at lagging power factor.

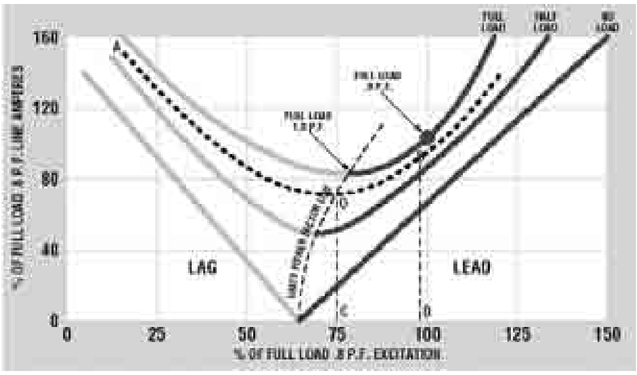

Figure 14: Characteristic "V" Curves

## IX. SYSTEM POWER FACTOR CORRECTION

By operating synchronous motors with a leading power factor, the overall system power factor can be shifted toward unity. The power factor of a synchronous motor can be controlled by varying the amount of excitation current delivered to the motor field during operation. As the DC field excitation is increased, the power factor of the motor load, as measured at the motor terminal, becomes more leading as the overexcited synchronous motor produces vars. If excitation is decreased, the power factor of the motor shifts toward lagging, and the motor will import vars from the system.

The decision for Lion Oil to go with a synchronous motor was based upon the need to minimize economic penalties due to poor power factor at the utility connection. An example is illustrated in Figures 15-17 of how penalties can occur.

Figures 15-17 show one-line diagrams of a synchronous motor operating at leading, unity, and lagging power factors. When operating at leading power factor as shown in Figure 15, the field excitation is increased above the level required to produce unity power factor.

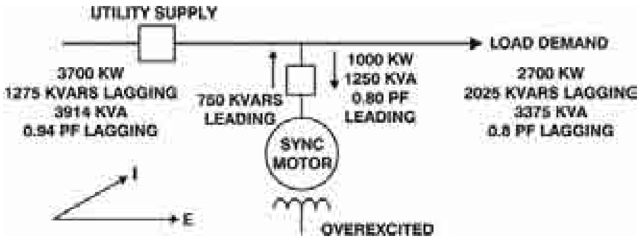

Figure 15: Synchronous Motor in Leading PF

If the power supply system is being operated to maintain a fixed voltage at the terminals of the motor, var production by the motor reduces the vars required from the system to maintain the preset terminal voltage.

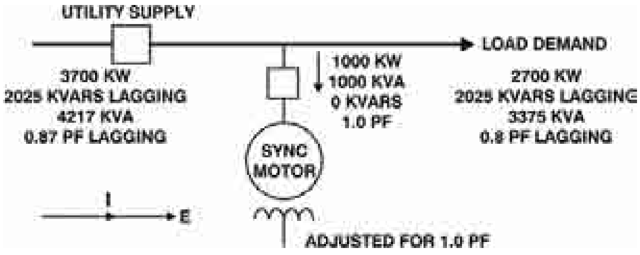

Figure 16: Synchronous Motor at Unity Power Factor

As the motor excitation is reduced until the motor operates at unity power factor (Figure 16), the supply current and voltage shift in phase. The kVA burden supplied to the utility increases from 3914 kVA to 4217 kVA; if excitation is further reduced, the motor will operate at lagging power factor and the system power factor will shift to lagging as well. Notice the kVA burden from the utility is now 4470 kVA. See Figure 17.

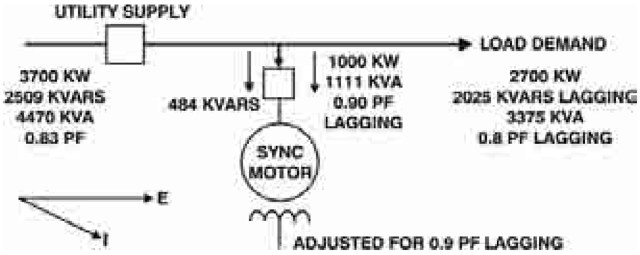

Figure 17: Synchronous Motor at 0.9 Power Factor Lagging

Under these conditions, the system must carry a larger kVA load than when the motor is operating at unity or leading power factor. At .8 lagging power factor, the system must provide the local var support. Thus, operation of the synchronous motor can substantially affect the power factor of the load as seen from the supply system, and the kVA of the load as seen from the utility system resulting in penalties because of low incoming power factor.

## X. EXCITATION SYSTEM CONTROLS THE POWER FACTOR

To take full advantage of the synchronous motor, it is necessary to have an excitation system that will maintain constant power factor regardless of load and AC supply variations to the excitation controller. Today's excitation systems are designed with features to help improve the quality of machine control. For this system, a digital controller was specified by the engineering consultant with the following features:

- Power Factor Control
- Under Excitation Limiting
- Over Excitation Limiting
- Manual Control

The digital control, however, also includes functions to provide added value to the plant and the maintenance personnel who are responsible for the system. These features include:

- Loss of Voltage Sensing and automatic transfer to manual control to prevent a machine trip caused by a loss of PT fuse at the controller input.
- Autotracking between Power Factor mode and Manual Control to avoid bumps and a system disturbance during a unit transfer.
- Oscillography, a diagnostic tool to evaluate plant issues such as a machine trip to help determine and locate the problem.
- Sequence of Events that tabulates all events that occur from the time the motor is started to the time the machine is shutdown.

### AUTOMATIC POWER FACTOR CONTROL

The digital controller is designed to maintain a specific cosine angle by measuring the real power into the motor and adjusting the excitation into the field to provide the correct amount of kvars to maintain the cosine angle. Figure 18 illustrates the constant angle as a function of Kw into the machine versus kvars out of the machine. Any voltage variation to the system or load change that would affect the power factor is immediately modified via the excitation system to restore the cosine angle and power factor of the machine.

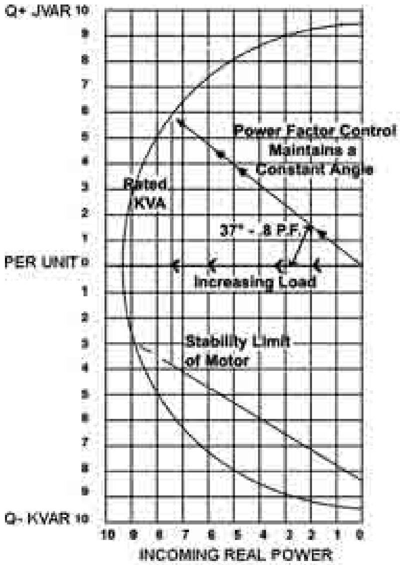

Figure 18: Motor Capability Curve

The automatic control eliminates the concern with an AC supply variation to the excitation system that could otherwise result in pole slip due to too little excitation for the motor field. Additionally, digital systems are equipped with safeguards to prevent pole slip from occurring. These include:

- Field Forcing Margins
- UnderExcitation Limiting
- OverExcitation Limiting

### FIELD FORCING

Field forcing provides a means to maintain constant voltage into the field even when the AC supply voltage drops as much 30-40%. Hence, if the field voltage required by the motor were 100 Vdc at .9 power factor lead and the digital controller were selected to provide 150 Vdc maximum ceiling voltage, the digital controller would be able to provide 100 Vdc to the field even if the supply voltage into the controller were to drop 50%. The additional margin could mean the difference between continue process control or a machine trip and plant outage.

### UNDEREXCITATION LIMITING

Digital controllers also are equipped with underexcitation limiters. These devices have always been popular for generators, but also very practical for synchronous motors using digital controllers. The underexcitation limiter monitors the kW into the synchronous machine as compared to the kvars being supplied. Should the kvars drop below acceptable levels needed to maintain synchronism, the underexcitation limiter will cause an increase in excitation to prevent a machine trip. Figure 19 illustrates an apparent drop in machine vars. Notice how the kvar drops to a level but is limited to any further reduction because of the underexcitation limiter.

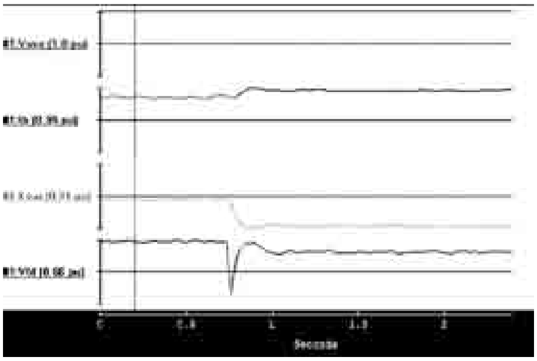

Figure 19: Underexcitation Limiter Operation for Synchronous Motor

### OVEREXCITATION LIMITING

To ensure that too much excitation is not applied into the rotor for extended periods of time, the excitation system is equipped with an overexcitation limiter. The overexcitation limiter monitors the field current and if it should remain too high for extended periods, the excitation limiter will react by restrict-

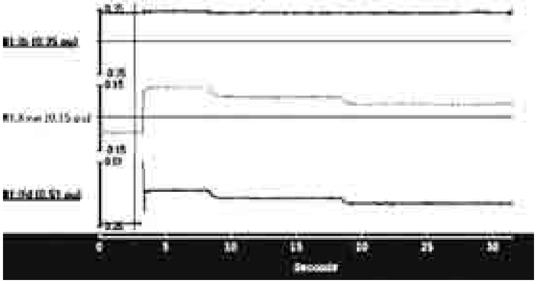

Figure 20: Overexcitation Limiter Operation on Synchronous Motor

ing any further increased field current and restore the level within a safe operating region for the machine. Figure 20 illustrates how a bump in the system has occurred and kvars are limited because of the overexcitation limiter limiting any further increases. Observe that the overexcitation limiter limits at three levels to allow short time var boosting that could benefit the system.

### OTHER FEATURES

Today's digital excitation controllers such as the type provided for Lion Oil also include field protection that might otherwise have been neglected or provided by other discreet devices. These additional features include field overvoltage and field overcurrent, as well as, over and under terminal voltage monitoring. Since Brushless motors use diodes to rectifiy the AC to DC from the exciter output, failure of these diodes can lead to a faulted exciter phase, and subsequent overload and excessive vibration of the exciter. See Figure 21. New digital controllers are equipped with diode failure detectors for the Brushless exciter that will alarm should failure occur and allow for a timely shutdown to repair faulted devices.

## XI. EXCITATION SYSTEM INTERCONNECTION

Unlike constant voltage supplies that require only an AC voltage source to provide a fixed DC into the field, the automatic control system requires inputs from instrument PTs for measuring motor line voltage and a current transformer signal input for measuring the reactive current out of the motor. See Figure 21.

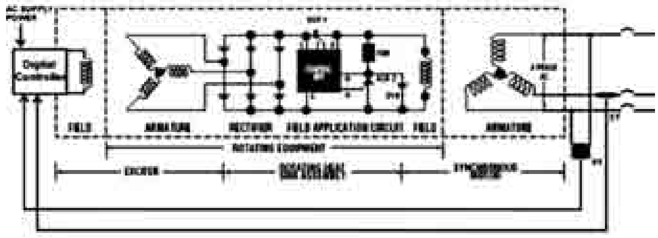

Figure 21 System One Line Interconnect

Inputs for starting the excitation systems are interfaced with the motor control, so when the motor breaker closes, the excitation system will apply excitation into the exciter field. The excitation system initially is enabled in manual control with a fixed DC current level to the field. Once the motor field is synchronized to the line, the system switches to power factor control for automatic operation.

Outputs are available to monitor any operation of the excitation limiters and general annunciation of any protection alarms either by hard contact or by a Modbus RS 485 serial port.

## XII. TESTING AND EVALUATING

During testing, V curves checks are performed to evaluate motor characteristics. Historically, the V curve was obtained by installing chart recorders and appropriate transducers to measure watts and vars. In the digital excitation system, curves can be obtained using the oscillography that can speed commissioning time and provide permanent records of the motor's history. Figure 22 illustrates kvars and AC line current when field excitation is changed forming a V curve of the synchronous machine. Notice how the kvars increase with increasing excitation. As the motor line current valleys between the two AC line current peaks, the kvars are zero. A further reduction in field current now causes the kvars to further decrease, causing a lagging AC line current and lagging power factor in the system.

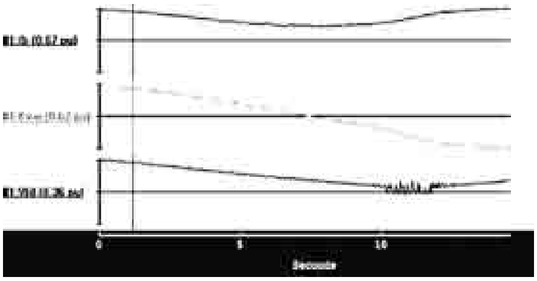

Figure 22: Testing the Synchronous Motor Operation using V Curve

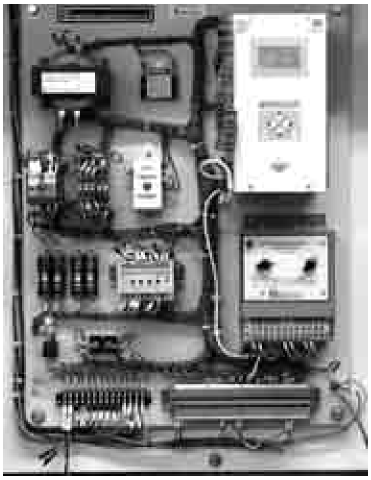

Figure 23: Picture of new excitation system.

## XIII. CONCLUSION

For low-speed applications and power factor concerns, the benefits offered by the synchronous motor can provide long term improvements that can represent cost savings to the plant. The brushless exciter favors a more streamlined control via a solid-state device to apply excitation to the field with increased reliability and economic benefits. Accurate control of the synchronous motor power factor as implemented by a digital excitation system offers more efficient control of the machine to help avoid potential machine trips due to low AC power supply variations to the excitation system.

Features included in the excitation system also provide more complete monitoring of the synchronous machine to safeguard the unit under abnormal operating conditions. Special attention should be provided for long time storage of the motor prior to installation to be sure the motor is adequately protected from moisture.

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# UNDERSTANDING THE TESTS THAT ARE RECOMMENDED FOR ELECTRIC MOTOR PREDICTIVE MAINTENANCE

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## ABSTRACT:

This article will discuss the root causes of electrical failures in motors and how high-voltage testing can help in early detection. The article will review the insulation resistance test, polarization index test, DC hipot test, and the surge test along with outline the types of problems they can and cannot find.

Most electrical failures are caused by a combination of the voltage spikes that occur at start-up and normal deterioration. The problem often begins as a turn-to-turn short that will eventually go to ground. Without high-voltage testing many of these problems will go undetected.

## I. INTRODUCTION

Before making a logical decision about what kinds of testing should be done on motors to predict electrical failures, it must be understood what makes these failures occur. It is important to understand the different insulation groups, the aging process of the insulation, and review typical failure scenarios. Only then can decisions be made as to which tests should be included.

## II. THE INSULATION GROUPS

The insulation system of a motor consists of the groundwall insulation, the phase-to-phase insulation and the turn-to-turn insulation. In a typical induction motor, the groundwall insulation is the slot liner paper that protects the insulated copper to ground. The Phase-to-Phase is often a sheet of insulation paper that is laid between the phases. The weakest link in the insulation system is often the turn-to-turn insulation. This is the enamel on the copper of a random wound motor or the enamel and tape found on form coils. This insulation's purpose is to protect from copper-to-copper failures.

To properly test the total insulation system, several different tests must be performed. The groundwall insulation can be tested with a megohmmeter to determine insulation resistance values, a polarization index test to evaluate the elasticity of the insulation, and a DC hipot to test the dielectric strength of the insulation to some predetermined level. The phase-to-phase insulation can also be tested with some of the same tests mentioned above if the motor is completely disconnected. In most predictive maintenance scenarios, this will not be the case and the phase-to-phase insulation must be tested in the same manner as the turn-to-turn insulation.

Surge testing is the only available test of the turn-to-turn insulation.

## III. THE INSULATION AGING PROCESS

The insulation aging process can be affected by one or more of these five factors:

Contamination: A chemical deposit on the windings that causes deterioration of the insulation.

Mechanical: Vibration or movement within the windings or the motor that wears the insulation system.

Normal thermal aging: The slow deterioration of the insulation over the winding's natural life through normal operation.

Early thermal aging: Excessive winding temperatures causing premature failure.

Overvoltage spikes: High-Voltage surges caused by switching, lighting, and VFD designs.

All five of these should be considered when designing a test program. We will look at the normal thermal aging process and how it is affected by Mechanical, Early thermal aging, and the Overvoltage spikes. For this article we will not deal with the contamination problems.

## IV. WHAT MAKES MOTORS FAIL?

Depending on which study is referred to; electrical failures are responsible for 35% to 40% of all motor failures. These same studies often show that many of these winding failures begin as turn-to-turn shorts caused by steep-fronted surges due to switching. These studies date back to 1936. Measurements of these surges began as early as 1960, showing spikes of 0.5 micro-seconds at up to 5 pu.

When discussing dielectric strength and voltage spikes in this paper, the measurement of "pu" will be used. One per unit (pu) is the peak line-to-ground voltage.

These steep-fronted surges are caused by a variety of sources. The most common and main cause of breakdown of the inter-turn insulation is switching surges. These switching surges can occur both when opening and closing the contacts. Restriking will create multiple surges.

Studies show that these surges will range from 1 to 5 pu with rise times of .1 to 1 micro second.

A 4160V motor will see surges of up to 17,000V.

In normal operation, a typical coil will only see 10 to 100V turn-to turn. Pashens law states that a difference of 350V is required to initiate an arc (see figure 1). With this small of a potential difference, a motor should not fail due to turn-to-turn shorts from normal operation. It is the combination of weak insulation and the steepfront surges that accelerate the natural deterioration of insulation eventually leading to motor's electrical failures.

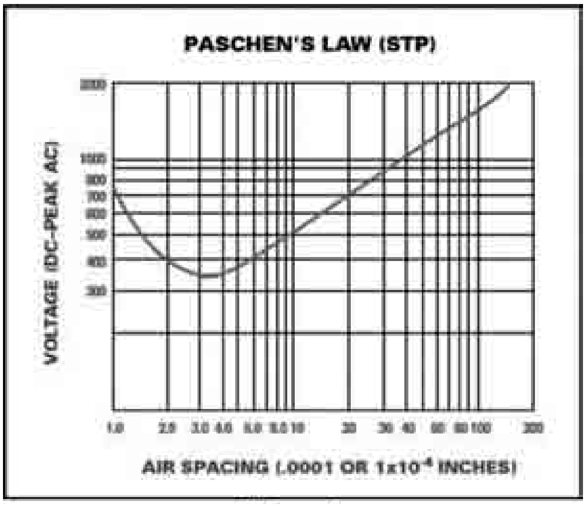

Figure 1

Mechanical abrasion within the winding is another deterioration mechanism operating on the motor's insulation. At start-up, a squeezing action caused by the magnetic forces will cause wear between the moving components. The magnetic fields changes 120 times a second causing this squeezing to occur each time. Even though wear does exist between the winding and the ground insulation, studies show that less than 17% of the ground insulation can be worn away due to this movement. It is the turn-to-turn insulation that is most affected by the abrasion.

As stated above, the potential difference in turn-to-turn during normal operation is not enough to cause a failure of the turn-to-turn insulation in a motor. Only the spikes will have a voltage level high enough to cause this kind of problem.

Adding to this turn-to-turn stress is the non-linear distribution of voltage across the phase. In a study conducted by Christiansen and Pedersen, it was concluded that the rise time of the spikes will determine how the voltage propagates over the windings. As shown in figure 2, the faster the rise time, the less linear the voltage divides over the coil.

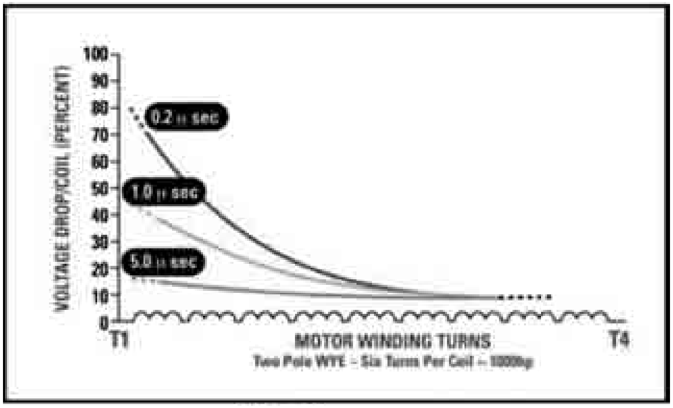

Figure 2

## V. TYPICAL SCENARIO OF AN ELECTRICAL FAILURE

When a motor is new, the dielectric strength of the insulation system is very high. On a typical 4160V motor turn-to-turn insulation strength is over 34KV. Over time, the insulation will deteriorate due to the normal thermal aging process. To accelerate this process, contamination and mechanical stress will cause a more rapid deterioration. This will continue until finally the insulation has deteriorated to a level that is affected by the surges (see figure 3).

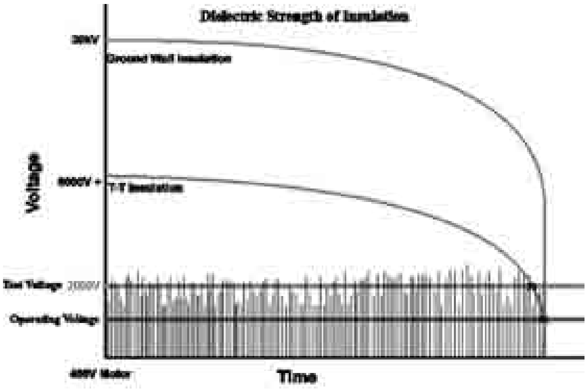

Figure 3

At this time, each surge will result in an arc causing more deterioration of the insulation.

When the turn-to-turn insulation erodes to a level close to the operating voltage, the conductors will weld together causing rapid failure due to the high induced current. (see figure 4).

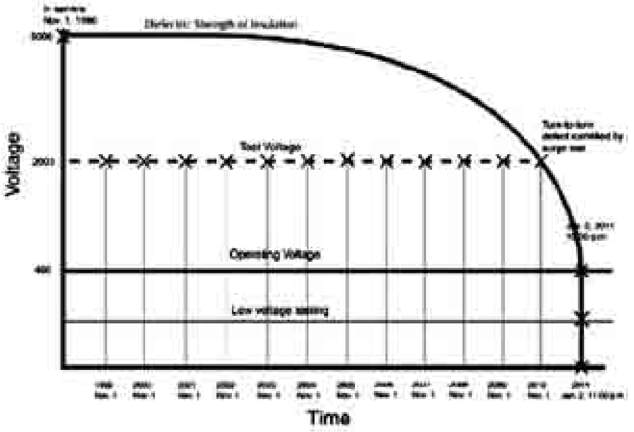

Figure 4

## VI. HIGH VOLTAGE TESTING?

Of the four tests reviewed in this article, only two are considered to be "high voltage". It is important to understand what each of these tests can and cannot do. It is the combination of the right tests that will help meet the goal.

### A. INSULATION RESISTANCE TEST

Developed early in the 20th century, the insulation resistance (IR) test is the oldest and most widely used test for assessing the quality of insulation to ground. In this test, the motor frame is grounded, and the test instrument (megohmmeter) imposes a DC voltage on the motor windings. Instrument readout is provided in megohms.

A sound winding yields a readout in hundreds, or thousands, of megohms. For random wound & asphalt Mica insulation, ANSI/IEEE Std 43 IEEE Recommended Practice for Testing Insulation Resistance of Rotating Machinery prescribes as a minimum acceptable reading 1 megohm plus 1 megohm per KV of the motors rated voltage. 100mΩ for modern form wound windings is acceptable. Minimum acceptable resistance for a 460V motor, for example, is 1.46 megohms. Prudence, however, dictates that the motor be removed from service for winding refurbishment while winding-to-ground resistance is still well above the minimum acceptable value.

IR test readings are highly sensitive to temperature and moisture. For accurate, meaningful readings, testing should be done when the motor has been out of service for a long enough time for it to have reached atmospheric temperature. To preclude condensation, the temperature should be above the dew point. IR readings obtained must then be corrected to a standard temperature in accordance with tables provided in the IEEE 43 formulae. This test is a test of the ground insulation only and has no value in determining the quality of the turn-to-turn insulation.

### B. POLARIZATION INDEX TEST

This ten-minute DC test is performed at a voltage lower than maximum testing voltage as per IEEE43. For more information of exact voltage levels see the table available in IEEE43.

A megohm reading is taken at one minute and again at ten minutes to determine the elasticity of the ground insulation. When placed in an electric field, molecules of the ground insulation should align with that field (see figure 5). If the insulation is aged, hard, and brittle, no polarization can occur.

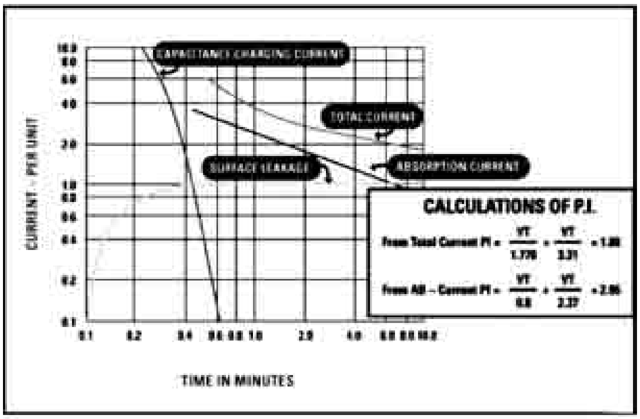

Figure 5

The Polarization index is the ratio of the ten-minute insulation resistance reading divided by the one-minute reading. Over the ten-minute period, this reading should increase by a factor of two or more giving a "PI" of two or more. If the insulation is very brittle, the polarization index will be one or very slightly more than one, indicating no polarization took place (see figure 6). This test also looks at only the ground insulation and will not see the problems in the turn-to-turn insulation.

### C. DC HIGH-POTENTIAL (HIPOT) TEST

The first of the two "high voltage" tests, the DC HiPot test can uncover insulation weaknesses that might not necessarily be detected in an IR or PI procedure. In addition to measuring overall insulation resistance to ground, it provides information on insulation dielectric strength. In this sense, it can detect insulation weaknesses that are likely to fault to ground if subjected to the high transient voltage surges that commonly occur on industrial power systems.

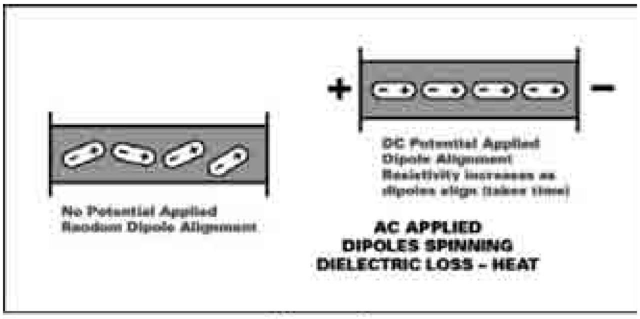

Figure 6

With this test, the motor frame is grounded, and a DC voltage gradually applied in step increments up to the maximum recommended test voltage. IEEE Std 95 Recommended Practice for Insulation Testing of Large AC Rotating Machinery With High Direct Voltage recommends maximum test voltage at 1.5 x 1.7 x Vline. At each step up to this voltage, leakage current in microamperes is read and plotted against the corresponding DC test voltage.

The resulting plot should be a straight line. Magnitude of leakage current and resulting slope of the line is not the only consideration. The criterion of importance is that the plot be, in fact, a straight line. An abrupt upswing in the slope of the plot indicates an insulation flaw. The test should be immediately aborted to prevent the winding from failing under test. The motor can be returned to service, but winding reconditioning or replacement should be scheduled for the earliest convenient opportunity.

The number of discrete steps in which the test is performed is optional. However, taking more steps in smaller voltage increments yields better results and minimizes the possibility of test voltage overshoot. Most DC high potential test sets incorporate overcurrent trips to protect the winding if a weakness is detected. The most sensitive of these overcurrent protective circuits can operate when leakage current is as low as one microamp. The DC HiPot is also a test that only looks at the ground wall and is of no value for the turn-to-turn insulation.

### D. SURGE TEST

Although surge comparison testing was developed more than 80-years ago, it is the newest of the classic tests performed to determine winding insulation condition. This test detects turn-to-turn, coil-to-coil, and phase-to-phase insulation defects that cannot be discovered by other methods.

Surge comparison testing is premised on the principle that in a stator with no winding defects, all three-phase windings are identical. This is useful for form wound stators without rotors installed. Each phase is tested against the others – A-B, B-C, and A-C. The test instrument imposes a brief voltage pulses on the phase undergoing the test and reflected ringing pulse are displayed on the instrument's oscilloscope screen. If the two windings are identical (as they should be), reflected images are identical and appear as a single trace.

This comparison method has been used in the motor shops repairing motors for over 40 years.

When using a surge tester as a predictive maintenance tool, the test does not require the comparison of two waveforms. A simpler test is performed that looks for a shift to the left by the waveform of the phase being tested. This shift indicates that the dielectric strength of the turn-to-turn insulation has deteriorated to a level below that of the switching surges. Once the insulation has weakened to this point, decisions need to be made concerning the future of the motor. With today's digital technology it is possible to acquire data of the phase under test at several voltage levels and nest them together.

This technique is valuable in detecting and documenting this shift to the left.

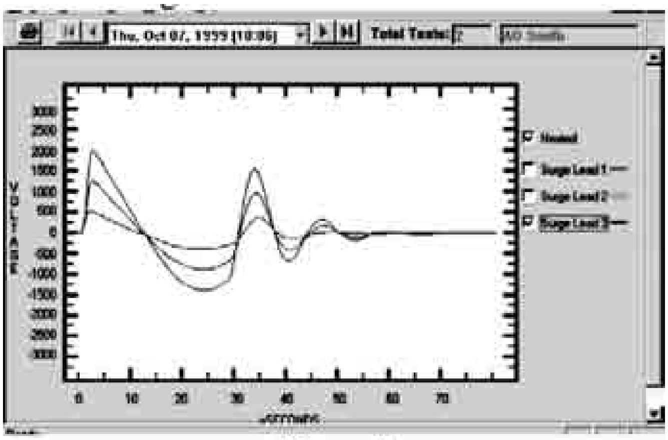

Figure 7

## VII. CONCLUSION

When testing a motor's insulation system, it is important that the right tests are performed.

Understanding that the motor sees voltages of up to 5pu, it is important that the insulation system be capable of handling stress higher than its normal operating voltage. As shown in this article, if high-voltage testing is not performed, it is nearly impossible to detect the weak insulation in advance of it's failing.

Of the four tests discussed in this article, three concern themselves with the groundwall insulation with no regard for the turn-to-turn.

The Surge test is the only test that looks at the turn-to-turn insulation. The turn-to-turn insulation is the root cause of a high number of the electrical failures. This test simulates characteristics of a surge at start up, making it an appropriate test.

# MAGNETIC FINITE ELEMENT ANALYSIS FOR A MOTOR PROTECTOR AND EDGE ARCING ELIMINATION

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## ABSTRACT

Undesired electric arcing has been problematic for many electro-mechanical switches and relays. In this paper, we first study the physics behind the arc damage, and then use a magnetic finite element analysis tool to determine best location and orientation for AC motor protectors. At the suggested mounting position, the damage resulted from edge arcing is minimized and the life of motor protector is extended significantly.

## 1. INTRODUCTION

The physics of the electric arcing is very complicated, and is beyond the scope of this paper. The ignition, maintenance and re-ignition of an arc depend on many factors, such as air/gas content, pressure, temperature, and humidity. The arc also depends on contact material, flowing current, and electric field strength in the vicinity of contacts. For DC problems, the arc is not desired as the circuit starts to open or close, while for most AC applications, the arc is intended to exist between two contacts until the current reaches zero.

An increasing imperative in all commercial manufacturing enterprises is increased effectiveness of the design process and robustness during manufacturing of the resulting design. In Sensors and Controls of Texas Instruments, one of the tools utilized to improve the quality of the products is multi-physics finite element analysis for mechanical, thermal, electromagnetic, and coupled problems [1,2,3].

For the product we are studying, the arc is also subjected to a strong magnetic field. Thus, the magnetic force generated on the arc (charges moving at high speed) is usually much larger than the electrostatic force that ignites and maintains the arc. This magnetic force drives the arc away from its designed arc path and may cause severe damages to the bimetal beam structure. Typical damage at its early stage is depicted in Fig. 1.

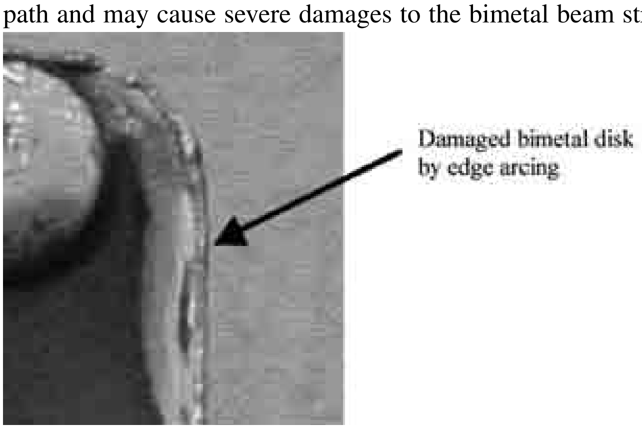


Fig. 1 Typical damage to the bimetal disk.

## 2. ELECTRIC AND MAGNETIC FORCES

When the condition permits, the electric field (voltage across the two electrodes) would stimulate the electrons' move from the negative (with lower potential) electrode to the positive electrode. If there is no magnetic field present, there are two forces acting on a charge. They are gravity and electrostatic forces. In the event of arcing, the gravity would be much smaller than the electrostatic force, and may be neglected.

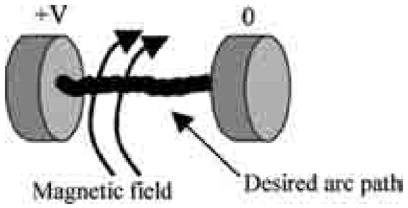
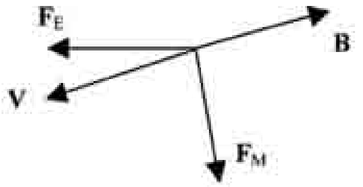


Fig. 2 Electrostatic and magnetostatic forces.



If there is no magnetic field, the desired arc path is shown in Fig. 2. However, with a magnetic field present, there are two possibilities,

- magnetic field has no effect to the arc path,
- magnetic field has an effect to the arc path, which depends on the angle between the magnetic field and the velocity as shown in Fig. 2.

If the magnetic field is parallel to the velocity, the magnetic force FM equals zero, therefore, the electrons would continue to accelerate along its moving direction. However, if the magnetic field is at an angle to the velocity, the magnetic force won't be zero and will have an effect on the arc path. The worst case is when two vectors are normal to each other.

## 3. MAGNETIC FIELD COMPUTATION AND BEST MOUNTING POSITION

Based on the electric and magnetic force analysis, the best orientation is when the desired arc path is parallel to the magnetic field. A 3D magnetic finite element model [4,5] was

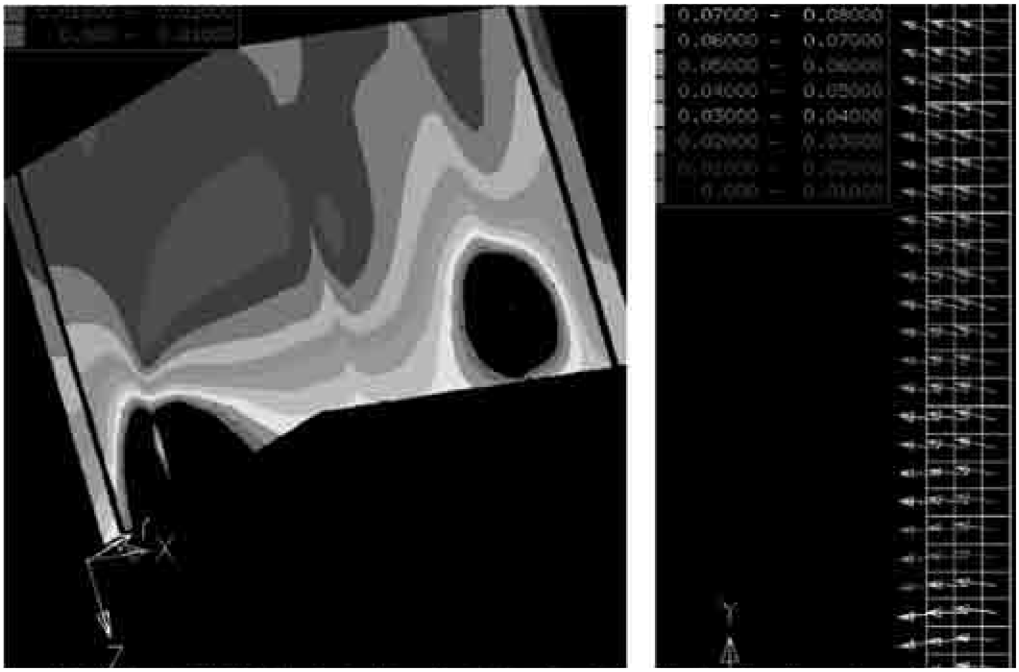


Fig. 3 Magnetic field behavior to determine the best location and orientation for motor protectors.

built to find the best mounting location and orientation. The best location is where the magnetic field is the weakest among the available mounting space. The best orientation is determined by the flux direction at the mounting location. Shown in Fig. 3 is the magnetic flux density contour and the vector field which are used to determine the best location and orientation.

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# ROOT CAUSE ANALYSIS OF MACHINE STATOR FAILURES

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## ABSTRACT

This article discusses the basic methods for root cause analysis of large rotating electrical machine stator failures. Several in service and test failure examples are presented.

## BACKGROUND

The first question asked by asset managers after a machine stator failure is when will it be returned to service. This information is critical for them to maximize plant operation.

However, operation and maintenance engineers need to know why the motor or generator failed and what can be done to prevent a reoccurrence in that machine or similar units. A failure root cause analysis of specific circumstances leading up to each failure is essential to understand the deterioration mechanism. With this knowledge, successful remedial action can be developed. If the machine is very large and critical to the economics of the site, then a visual inspection of the failure by a seasoned expert with that type of machine is required for the best results. There are very few experts in the industry that understand and can identify the variety of deterioration mechanisms that result in stator failures. If time of casts does not permit input of a specialist, then the failure should be examined by someone with some understanding of rotating machine insulation systems. There are formal "root cause" training programs available, but these are often just a method to list all possible conditions that can result in deterioration and not those specific to the machine in question. An understanding of machine design, operation conditions, maintenance history and the experience of similar designs are all critical to arriving at a correct conclusion. You cannot take too many digital photographs as the investigation unfolds.

## OPERATION INFORMATION

Records of machine operation immediately before a failure can provide information on why a stator failed even before an inspection is conducted. Was there a storm in the area? Was there a temperature, speed, vibration or load excursion? Past operation information must also be studied. Has there been a trend of increasing temperatures or increasing partial discharge activity. Has the winding been in service for several decades or is it new? Large rotating electrical machines are complex devices and failure mechanisms can be equally complex. Often there are several types of deterioration occurring simultaneously.

Determining the real root cause of a failure requires careful analysis of data collected before the event. No prior indications of developing problems are also important.

## DETERIORATION MECHANISMS

Stator deterioration mechanisms can be classified into a few general categories.

1. Thermal deterioration due to operation at temperatures higher than the insulation system can safely withstand.
2. Electrical stress (short term or long term) higher than the insulation system can safely withstand.
3. Mechanical stress from movement or vibration of the winding.
4. Contamination of the winding with dirt or moisture.
5. Inadequate design, manufacturing QA processes or material application.

## DISSECTION

Dissection of the failed stator bar or coil is essential. Dissection of adjacent bars and coils that did not fail is also essential. Usually the deterioration that resulted in a failure is also present throughout the winding. This deterioration is often at various stages of development at other parts of the stator winding. Do not scrap the removed winding until it is clear no additional understanding of the deterioration can be gleaned from the pieces.

## FAILURE OF A NEW WINDING

After the completion of a small hydro-generator stator rewind, a coil failed before the final 2E+1 voltage was obtained. The defective coil was removed and replaced with a spare. The coil supplier and the generator owner needed to know why the coil failed and if the rest of the winding was at risk.

The failure exit point was quickly located just inside the core near the top. There appeared to be a crack in the conductive armor tape near the failure. There were no other abnormalities present on the surface of the specimen. The remaining stator coils were able to withstand the desired overpotential test.

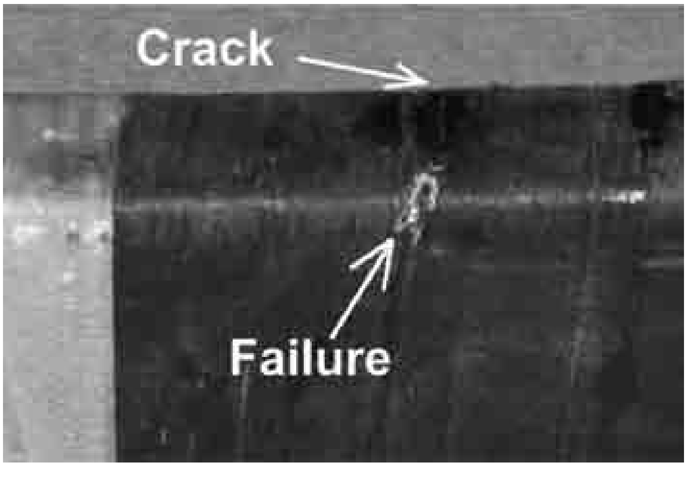

FIGURE 1: A stator coil failed during the final acceptance overpotential test.

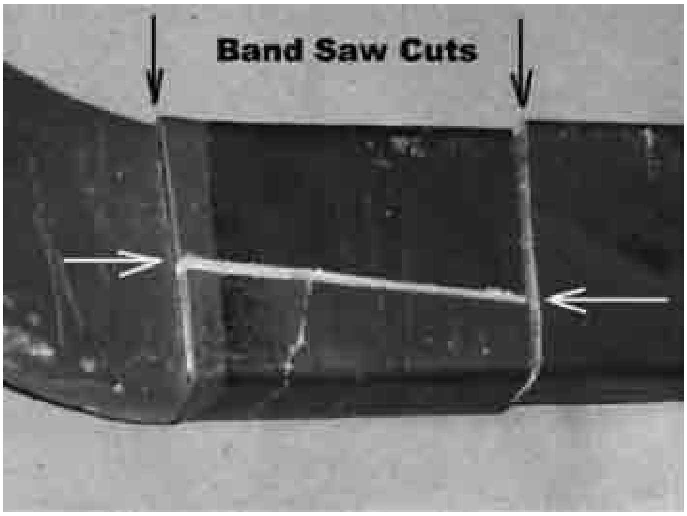

FIGURE 2: Black arrows show cuts made to isolate the failure site. White arrows show the cut that permits insulation removal from the sample.

One of the first decisions was to determine how to isolate the failure area. Failures often do not progress straight through insulation but follow weaknesses between tape layers.

Isolation cuts should be made no closer than 2-3 cm from the failure site. Once removed, two additional cuts must be carefully made to permit lifting the groundwall insulation from the conductor stack.

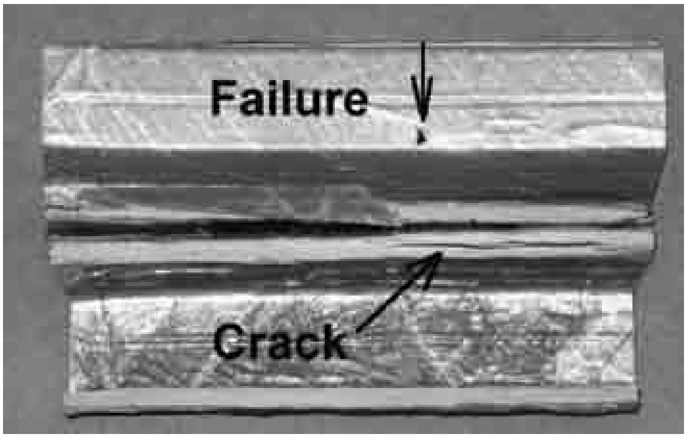

FIGURE 3: Groundwall insulation was easily folded away from the conductor stack.

A telltale black puncture spot indicated this failure started at the conductor stack edge. This is a high-voltage stress area and many failures start at a corner. It was also apparent the surface crack penetrated through all tape layers at this location and was the cause of the dielectric failure. Another problem was also uncovered. Groundwall insulation tape layers were well bonded together but not bonded to the conductor turn tape.

With an insulation fracture across as well as along the groundwall insulation, it is apparent the coil endarm was twisted during installation. A weak resin bond between conductor stack and groundwall insulation was not adequate to prevent mechanical then electrical failure of groundwall insulation.

ROOT CAUSE: Fracture of groundwall insulation during coil installation. Lack of bonding between tape layers was a major contributing factor.

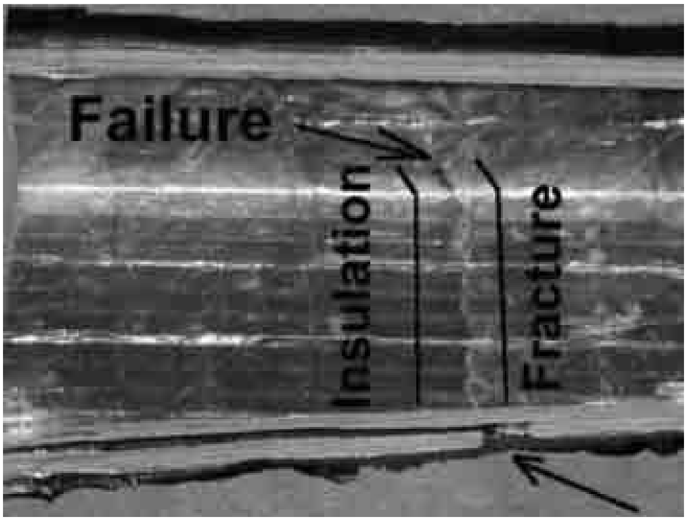

FIGURE 4: In this view we can see the fracture completely circled the coil insulation.

## IN SERVICE FAILURE OF A MATURE WINDING

A 1912 vintage generator that was operating with epoxy-mica stator coils installed in 1986 failed during a thunderstorm. This machine does not have a step-up transformer and the generator leads are 3 miles long following the river to the next site and a tie to the local 138kV system. There is a history of lightning induced stator failures.

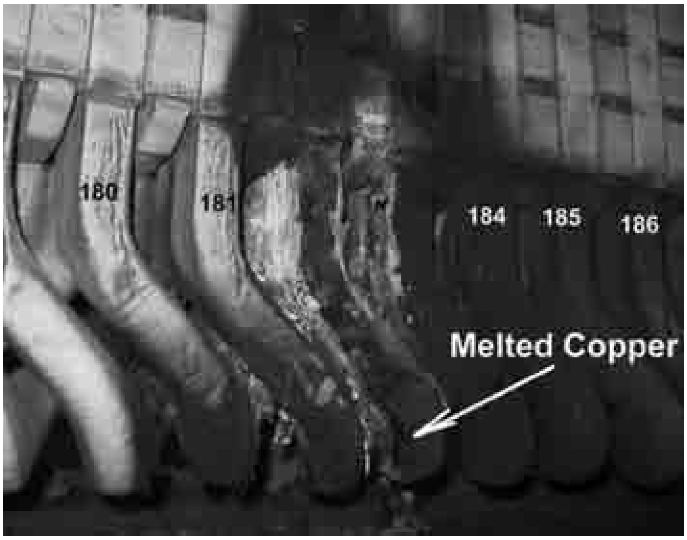

FIGURE 5: With the rotor removed stator winding damage was found to be extensive.

The failure burned for a period of several minutes and melted a great deal of copper out of slot 182. Coils against rotor rotation from the failure were not damaged. There was no damage to coils before coil 178. Coils after 182 suffered fire damage. The failed coil and adjacent damaged coils were removed and replaced with half coil splices.

The two coil sides involved in this failure were placed on a table and positioned as they were in slot 182. In Figure 6 we are looking from the back towards the machine bore. The failure appeared to have started on the first inside turns at the lower end arm of top coil 179 just below the core edge of slot 182. Circulating currents become very high and the melted copper

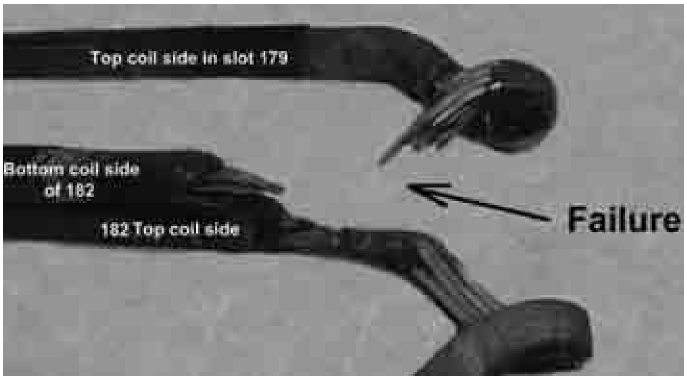

FIGURE 6: This failure created a sphere of missing copper. The center of this ball indicates where the failure originated in the bottom coil in slot 182.

shorts adjacent turns. The fault is maintained within the thick mica insulation until the pressure and heat burns into the top coil in slot 182. Phase 3 is now open. No ground fault developed. The generator is removed from service due to imbalance phase currents.

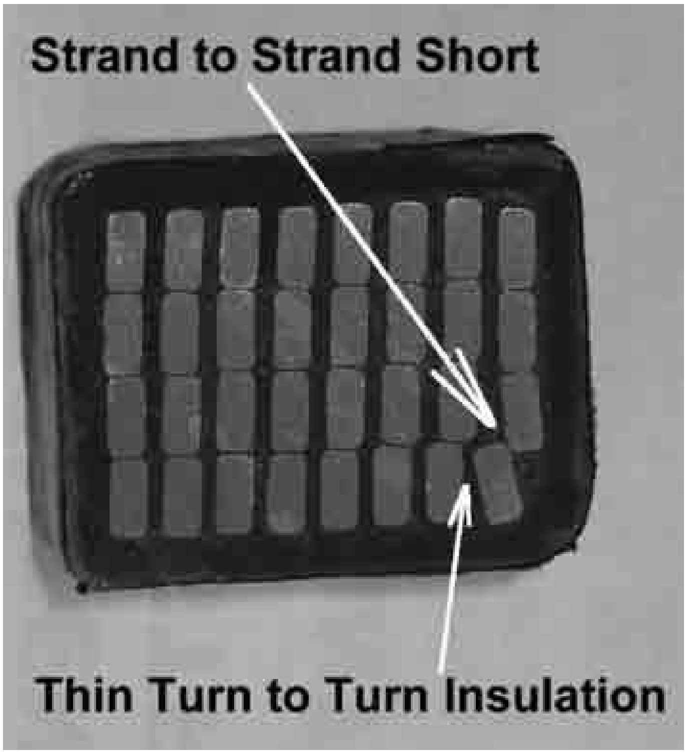

FIGURE 7: Dissection of adjacent removed half coils found strand defects and voids in the insulation.

Dissection of several removed half coils found two strands on the first turn crushed together and shorted. Note there is misalignment in the second turn strands as well. Voids are present at the interface between turn insulation and main groundwall insulation. There was also slightly thinner turn insulation between the first and second turns due to the twisted strand.

There were numerous voids and tape folds in the endarms but this is a low operating dielectric stress area where voids have little effect. This is not the case during a voltage surge when endarm turn-to-turn voltages can be very high.

ROOT CAUSE: A twisted conductor strand in the original construction may have resulted in a strand-to-strand short resulting in localized heating. Thinner turn-to-turn insulation may have also been present at this location. A lightning surge failed the coil due to the original defects and time related deterioration of turn-to- turn insulation in this one coil. Winding replacement was recommended.

## MATURE WINDING TEST FAILURE

During the 120% overpotential maintenance test of a 1955 vintage steam turbine generator, one stator circuit failed. These machines had been exceptionally trouble free with a history of only minor stator maintenance. The bar was removed and breakdown site dissected.

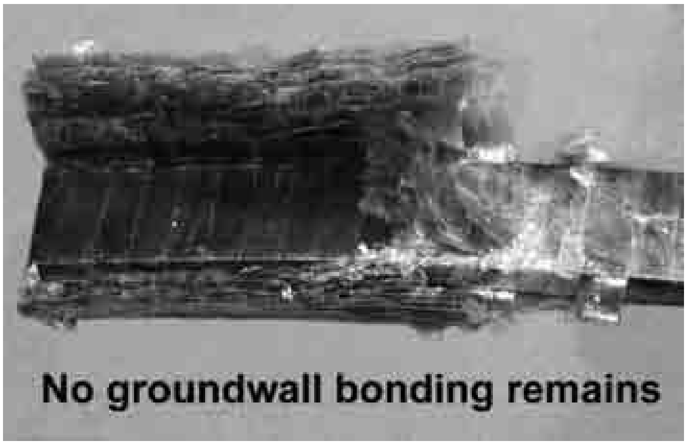

FIGURE 8: Dissection of the failed stator bar found no bonding between tape layers.

This generator was constructed with the first synthetic resin polyester bonded groundwall insulation. None of the original polyester resin remained to bond layers of mica flake insulation after 50+ years of service. The resin had returned to the original constituent oils.

ROOT CAUSE: Time related deterioration of the base resin. Rewinding all eight similar generators was recommended.

## MATURE WINDING TEST FAILURE CASE TWO

During a 130% maintenance overpotential stator test prior to rewedging, one phase of a 20 year old pump-generator winding failed. The coil was removed and bypassed. The other two phases were not tested and the stator rewedging project was cancelled. This was a severe duty machine with several starts each day. These stator coils had indications of minor corona activity and surface corona burns had been repaired several times.

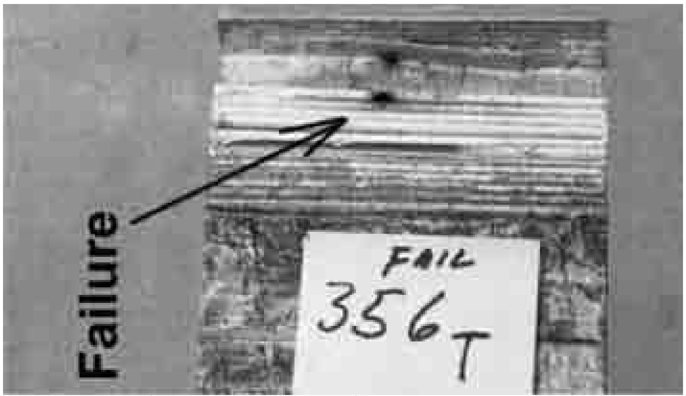

FIGURE 9: This test failure started at a corner of the top turn conductor stack.

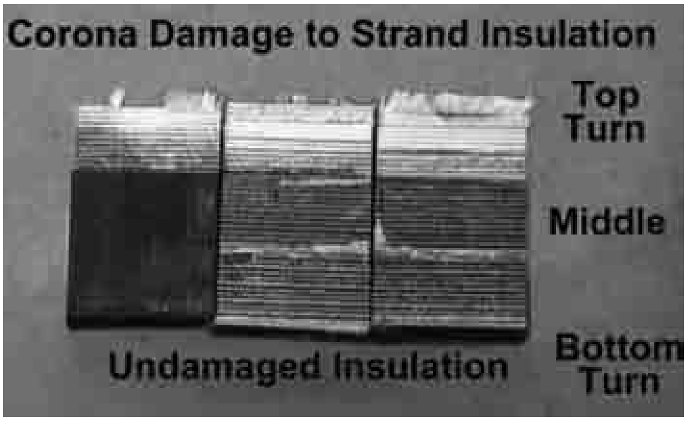

FIGURE 10: Additional cuts along the failed coil found internal corona had destroyed most strand insulation on the first turn near the machine bore.

The topmost stator winding conductors operate at the highest temperatures and ozone deterioration is accelerated by the increased temperature. There was some minor damage to the middle turn and no strand insulation to the bottom turn. Loss of strand insulation will create circulating currents and the increased losses add additional heating. Eventually a turn-to-turn failure develops and the coil fails.

ROOT CAUSE: Age related internal corona activity destroyed the strand insulation and weakened adjacent groundwall insulation. Rewinding both similar pump-generators was recommended.

## VIBRATION SPARKING FAILURES

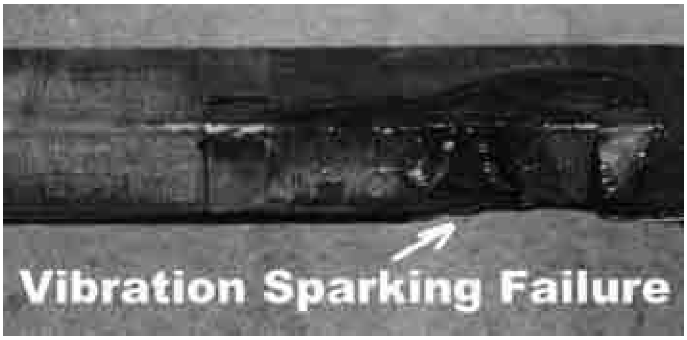

FIGURE 11: These motor coils appeared to have rodent damage in the slots.

A series of new 7000 hp, 4 kV motors experienced multiple stator coil failures after three years service. The filler strips and side packing were of a material not able to withstand the operating temperatures. The coils became loose and there was minor vibration in the slots.

Pitting and erosion of the bottom of the bottom stator coils resulted from vibration sparking.

## VIBRATION SPARKING CASE TWO

Several half coils removed from a failed 3,000 hp, 4 kV motor were dissected for an analysis of the test failure. These are very unique coils made only a few years by one OEM. A red silicone rubber tape was applied as the only groundwall insulation. There is no mica in this insulation system.

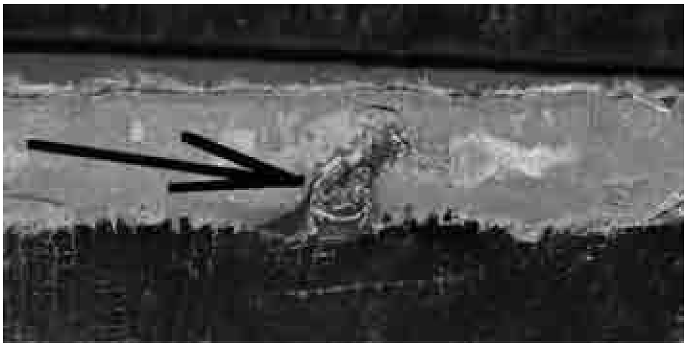

FIGURE 12: The motor coil failure location was apparent. Note all varnished glass armor tape is gone on the bottom of this coil.

This was a dielectric failure starting at an edge of the conductor stack then progressing straight through the insulation. There was no obvious deterioration of the rubber insulation other than on the bottom edge of some samples. There appeared to have been in-service coil movement and the resulting vibration sparking removed small pieces of insulation. There was severe time/temperature related mechanical strength deterioration of the glass armor tape and black varnish coating. There were numerous voids between the conductor stack and the groundwall insulation. The bond between the red silicone rubber and the conductor stack was gone in many locations. This permitted copper vibration within the insulation, the resulting vibration sparking on the higher voltage coils reduced insulation thickness.

Materials other than the red rubber had the typical thermal deterioration associated with 30+ years of service. Deterioration of the silicone rubber insulation thickness resulted from movement between the top and bottom coils in the slot. This resulted in abraded armor tape and vibration sparking of the insulation causing the test failure.

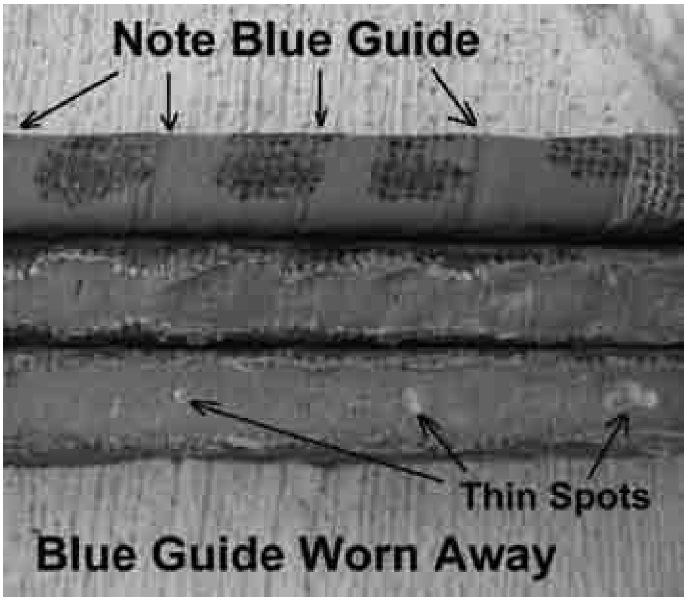

FIGURE 13 Three coils placed side-by-side show the progression of vibration damage on the bottom coil sides.

When glass armor tape was removed from one coil, the blue tape overlap guide was apparent (first coil). With the second coil the in-service coil vibration has removed the armor tape and some of the red rubber tape. In the third coil, thin spots in the rubber are present but a failure had not yet developed.

ROOT CAUSE: These two failures occurred 30 years apart but in both cases slot filler materials had deteriorated and permitted coil movement. Vibration sparking deterioration was faster than the usual mechanical abrasion of groundwall insulation,. Rewind all similar motors was recommended.

## SUMMARY

Performing the root cause analysis of stator failures is a necessary step in preventing additional incidents. Anyone with a basic knowledge of insulation systems and a curious nature can gain some understanding of why the system deteriorated and failed through a few simple dissection techniques. You can never take too many digital photographs!

Seasoned engineers familiar with the type of machine in question may also improve their confidence level and offer additional insight in failure mechanisms.

## BIOGRAPHY

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# IMPLEMENTING EMBEDDED SPEED CONTROL FOR BRUSHLESS DC MOTORS

Yashvant Jani, Renesas Technology America, Inc.

Brushless Direct Current (BLDC) motors, also known as permanent magnet motors, are used today in many applications. A new generation of microcontrollers and advanced electronics has overcome the challenge of implementing required control functions, making BLDC motors more practical for a wide range of uses.

In this series of articles we will discuss the basics of BLDC motors, including their construction and operation, fundamental equations for force and torque generation, along with basic control electronics necessary for proper deployment.

Also covered here is 120-degree modulation and a six-step method for operating the motor, as well as how the modulation can be implemented using Hall sensors and back-EMF signals. Included are implementation examples that make use of a microcontroller unit (MCU), as well as a discussion of the necessary features of on-chip timers and interrupt handling within the MCU.

## BLDC FUNDAMENTALS

A BLDC motor has two main components: a rotor made up of permanent magnets and a stator with a winding connected to the control electronics. The brushes and commutation ring that are essential parts of a universal motor have been eliminated from the BLDC motor design. Instead, control electronics are used to generate a proper sequence for commutation.

Because of its design, the BLDC motor is also known by other names: permanent magnet synchronous motor (PMSM), brushless permanent magnet motors, or permanent magnet AC (PMAC) motor. Sometimes it is simply called a PM motor.

The BLDC motor is based on a fundamental principle of magnetism, which tells us that similar poles repel each other, while opposite poles attract. As Figure 1a below illustrates, when a current is passed through two coils, it generates a magnetic field with a polarity that creates torque on the central magnet—in this case, the rotor.

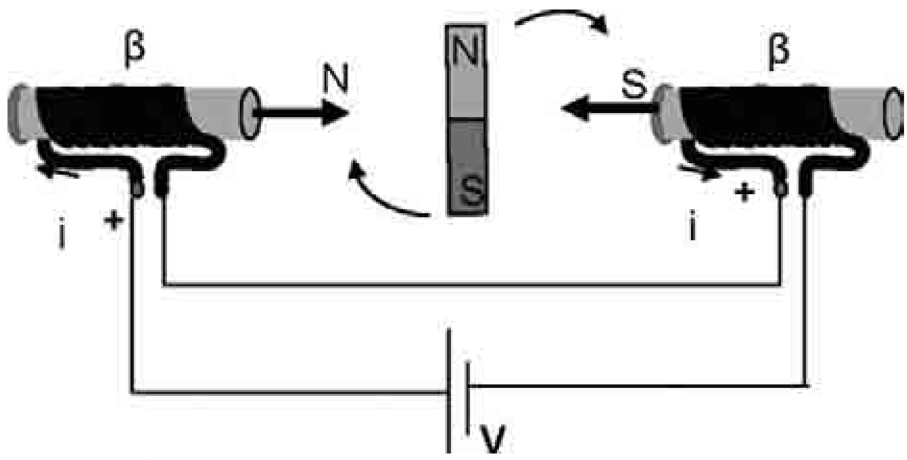

Figure 1a. Magnetic filed due to current in stator coils creates torque on the rotor.

When a current is passed in the direction shown, the central rotor rotates clockwise. When the rotor reaches a certain position, the direction of the current is changed so that the torque continues further in the same direction. When necessary, the current direction is changed again to continue generation of the torque.

However, instead of two coils, actual BLDC motors typically use six coils positioned 60 degrees apart, as indicated by Figure 1b, below. Then, two coils at a time can be energized to create a torque sufficient to move the rotor to a desired position. When this position is reached, other coils are energized to continue producing the torque.

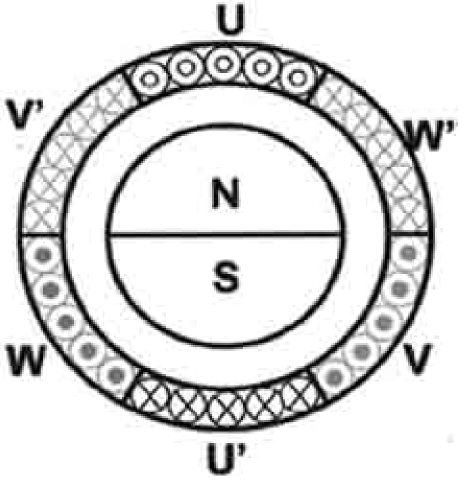

Figure 1b. Single pole pair 3-phase motor has six stator coils.

The total amount of torque created on the rotor is calculated using the Lorentz force formula in scalar form:

$$\text{Torque } T = r^*F = r^*(i^*L^*\beta^*\text{Sin }\theta).$$

Here, **r** is the moment arm of the rotor, **i** is the current passing through stator coils, **L** is the length of coil, is the magnetic field of the rotor, and **(theta)** is the angle between the current direction and the magnetic field of the rotor. The larger the current, the larger the torque in the motor because the magnetic field and winding length remain the same once the motor has been constructed. Designers have only one quantity to change during motor operation: the current.

In vector form, this formula is **T = r x F**, where all three quantities are given in vector form with magnitude and direction. This formula is important because it allows designers to create an algorithm based on vector formulation when they want to control torque and the flux in the motor.

A BLDC motor offers many advantages over other types of motors. Its speed is not impeded by the stress limitations of brushes. Because it has no brushes to create sparks, the motor can be used in hazardous environments. It is efficient, reliable, and generally low maintenance. The torque-speed relationship is linear. Also, a high torque-to-volume ratio means that a BLDC motor requires less copper (metal) than do other motor types.

BLDC motors do have some drawbacks, though. Rotor position information is required for proper operation, so either Hall sensors or a back-EMF signal with intelligence must be used to obtain this information.

In general, the motor requires external power electronics, whereas an AC induction motor achieves constant-speed operation when started from and driven by an AC power supply. The BLDC motor is a 3-phase device. As such, it requires an inverter and, thus, a power switch. Its rotor requires magnetic (rare-earth) metal, so it may cost more. Finally, incorrect control of a BLDC motor, especially at high temperatures, can damage its permanent magnet, so careful design of the control electronics is essential.

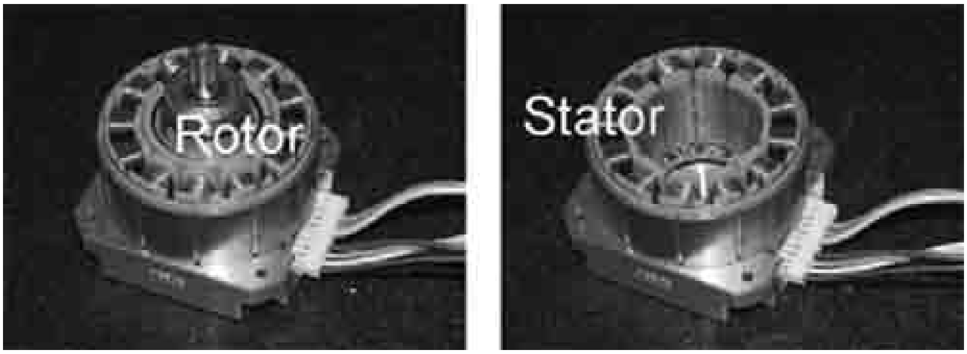

Figure 4. Small Brushless DC motor for appliance applications. BLDC motor control

Despite these drawbacks, use of BLDC motors abounds in the industry. Several examples are illustrated in the following figures. Figure 2 below shows the GE Electronically Commutated Motor (ECM), which has 12 poles (six pole-pairs) and comes in various horsepower ratings. Its electronics are mounted at the end of the motor in a case that is the same diameter as the motor itself. The GE ECM is a 3-phase motor that accepts a single-phase AC supply. Its stator has 18 coils and the rotor has surface-mounted magnets. Notice that the rotor is located inside the motor and stator is on the outside.

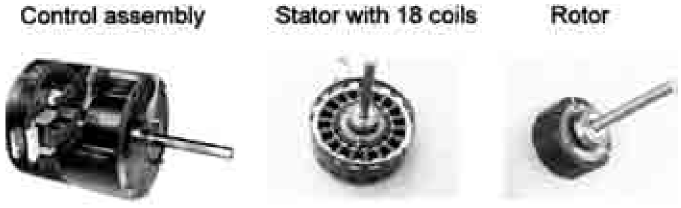

Figure 2. Electronically Commutated Motor (ECM) with control assembly

In contrast, the pancake motor shown in Figure 3 below positions the rotor on the outside and the stator inside. The rotor has several surface-mounted magnets, and the stator has many coils.

The small, low horsepower motor shown in Figure 4 below has external stators and internal rotors. All of these BLDC motors offer high torque and low volume, giving them an edge over universal or AC induction motors for applications in small spaces.

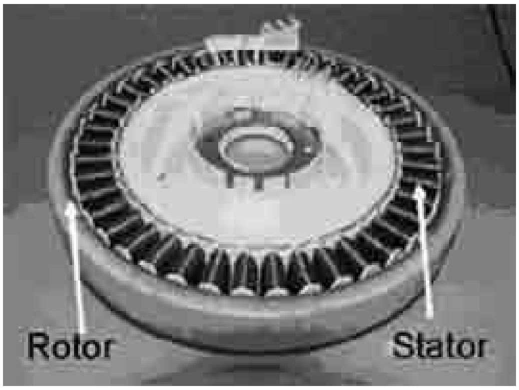

Figure 3 Pancake motor assembly shows stator and rotor

In Figure 5a below we see that the stators in 3-phase BLDC motors are connected in a Y or a star formation. All three phases are connected in the center, which is called the neutral or 1/2 $V_{dc}$ point. For this type of connection, the sum of the currents in all three phases is zero. Note that only two currents have to be measured; the third can be derived easily.

$$1_{sa} + 1_{sb} + 1_{sc} = 0$$

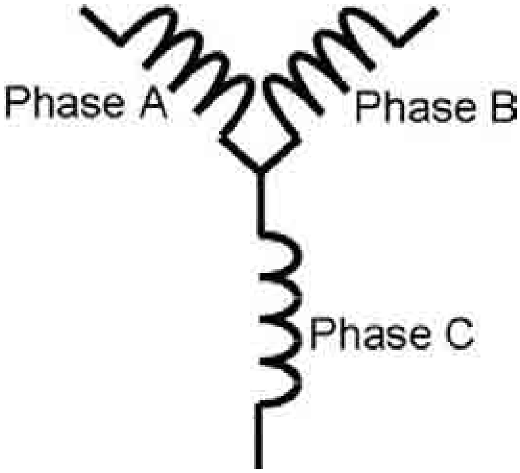

Figure 5a. Star or Y-winding for the stator has sum of currents equal to zero

The stator-per-phase circuit shown in Figure 5b below has one inductive element and one resistive element. Its torque is proportional to the current as long as the magnetic field does not change.

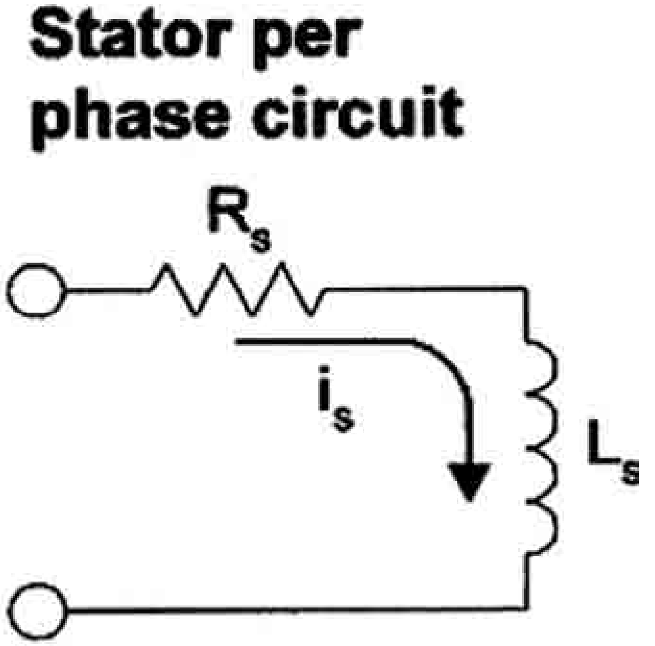

Figure 5b. Stator equivalent circuit.

In this case, torque is **T = k $i_s$**, where **k** is constant, **(theta)** is the magnetic field, and **$i_s$** is the stator current. If we combine **k** and **theta** we can write simply **T = K * $i_s$**, where **K** is known as the torque constant.

The amount of current passing through the stator coils is based on the voltage applied and the back-EMF voltage generated. As the motor starts rotating, it generates more back-EMF voltage, which reduces the current and results in less torque.

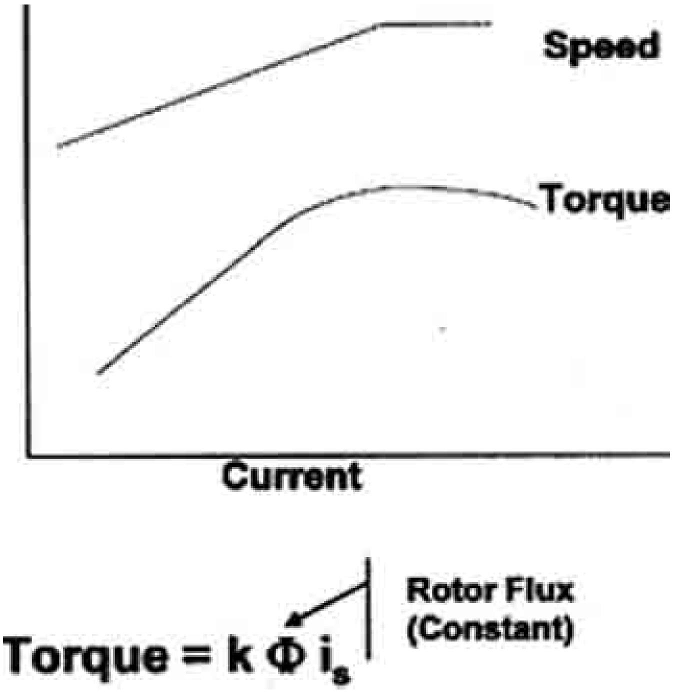

Figure 5c. Torque and speed increases as current increases in the stator coils.

The diagram in Figure 5c below shows that as the current increases, speed increases up to a certain point and then becomes constant.

Torque increases up to a certain point and then decreases. This behavior is typical in a BLDC motor. Flux is pre-established by the magnetic field of the rotor. Therefore, torque is controlled simply by controlling the current in the stator. The commutation sequence ensures that the rotor rotates in synchronization with the stator excitation.

Typical hardware used to control a BLDC motor are the converter and inverter as shown in Figure 6a, below. Six power-MOSFET or insulated-gate bipolar transistor (IGBT) switches are used in the inverter. When AC to DC conversion is not required, a DC supply can be connected directly to the inverter board. A typical BLDC motor drive configuration is shown in Figure 6b, below. Notice that the power switches are labeled S1 - S6 in this figure. They have other common names, which can be used according to the author's preference, thus

S1 = Up = U+ = A+
S2 = Un = U- = A-
S3 = Vp = V+ = B+
S4 = Vn = V- = B-
S5 = Wp = W+ = C+
S6 = Wn = W- = C-

A BLDC motor also has sensors. For example, Hall sensors and an encoder may be used to provide information about the position of the rotor. These sensors are not connected with the commutation and control portion of the inverter and MCU.

However, because the MCU must process signals from these sensors, they must interface with the MCU. Hall sensors and the encoder are connected to the rotor, and rotation is necessary to create Hall signals.

Back-EMF signals are created from the high side of the phase voltage using a resistor ladder. Current can be measured using DC current transducers (DCCT) or AC current transducers (ACCT) with phase wires passing through the coils. Additionally, certain techniques allow single-phase currents to be measured using a shunt resistor. The back-EMF and DCCT/ACCT or shunt resistor are connected to the stator.

In motor terminology, control based on Hall sensors and an encoder is known as control with sensors, while control without these elements is known as sensorless control.

## 120-DEGREE MODULATION AND COMMUTATION SEQUENCE

As Figure 1b earlier illustrates, a BLDC motor has six coils with phase settings generally denoted as Up, Un, Vp, Vn, Wp, and Wn. (Alternatively, we can use U+, U-, V+, V-, W+, and W- to indicate these settings.)

Three Hall sensors are located 120 degrees apart around the stator. Depending on which magnetic field passes over each sensor, the output may be high or low. When the north pole passes over a sensor, its output is high or state 1. When the south pole passes over a sensor, its output is low or state 0. Hall sen-

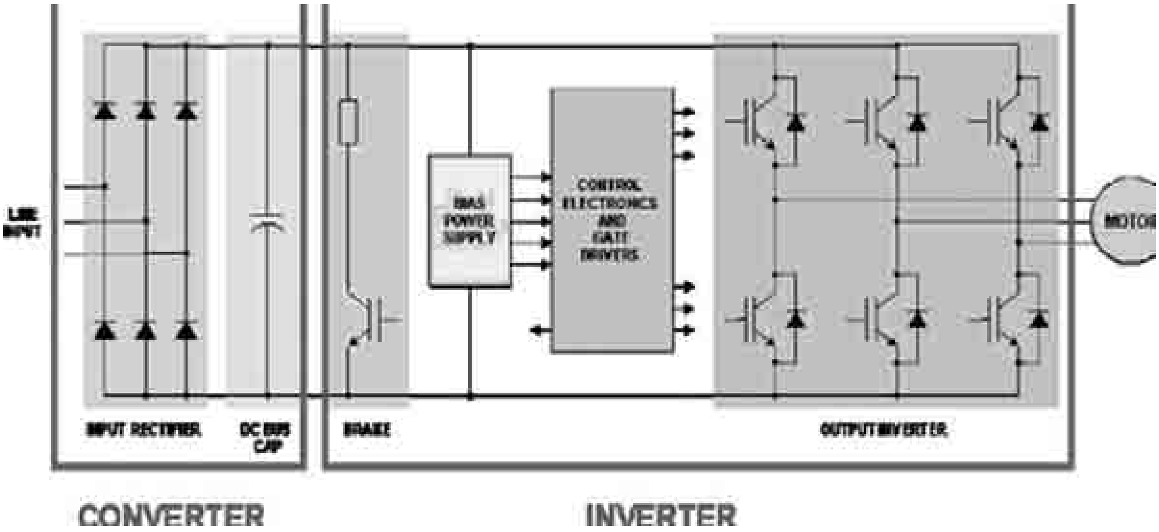

Figure 6a. Typical hardware layout with converter and inverter modules.

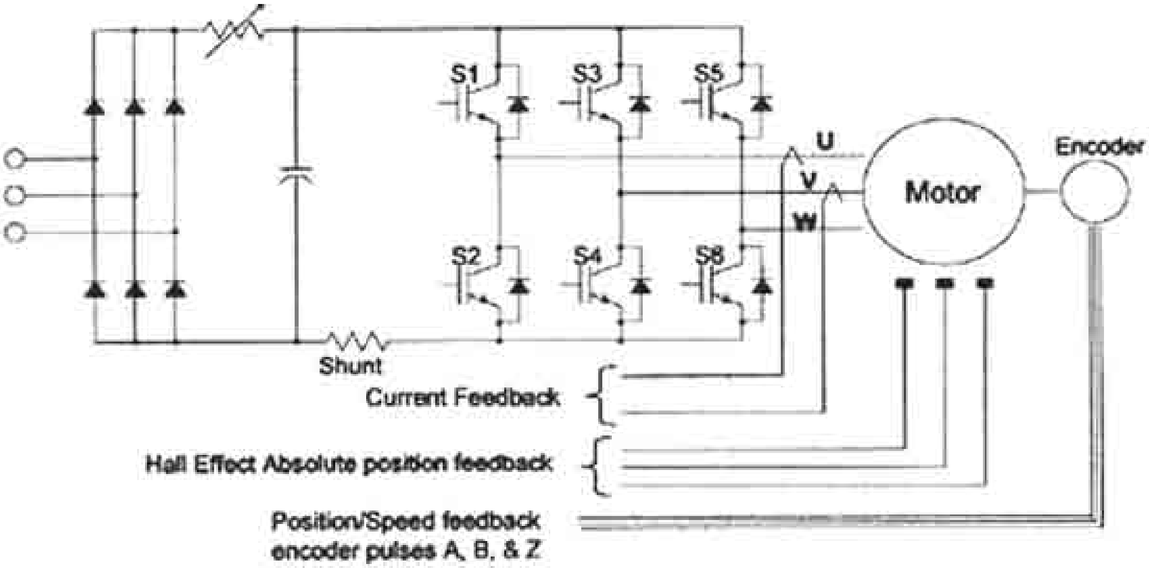
S1
S3
S5
S2
S4
S8
U
V
W
Motor
Encoder
Shunt
Current Feedback
Hall Effect Absolute position feedback
Position/Speed feedback encoder pulses A, B, & Z

Figure 6b. Typical representation with six switch configuration.

sors thus provide information about polarity and position.

A six-step commutation sequence is used to steer the current and produce torque. The sequence starts with the initial position of the rotor aligned properly at 0 degrees. Power at the coils U+ and V- is turned on. This excitation creates a magnetic field so that the rotor turns in the intended direction—towards the 60 degree position. When this position is reached, V- is turned off and W- is turned on. Because U+ is still on, the U+ and W- coils are excited, and torque continues in the same direction.

When the rotor reaches the 120-degree position, U+ is switched off and V+ is switched on. W- is still on and so the V+ and W- excitation continues to produce torque in the same direction. At the 180-degree position, W- is turned off and U- is turned on, while V+ is kept on. At 240 degrees, V+ is turned off and W+ is turned on, with U-kept on. At 300 degrees, U- is turned off and V-is turned on, and W+ is kept on. Finally, when the rotor completes a 360-degree rotation, W+ is turned off and U+ is turned on, with V- kept on. Thus, we are back to the original state or step 1.

These six steps, depicted in Table 1, below, form the commutation sequence that produces correct rotation in one direction. For rotation in the reverse direction, the steps are executed in reverse order: 1, 6, 5, 4, 3, 2 and back to 1.

| Step # | Phase Up | Phase Vp | Phase Wp | Phase Un | Phase Vn | Phase Wn |
|---|---|---|---|---|---|---|
| 1 | Up | | | | Vn | |
| 2 | Up | | | | | Wn |
| 3 | | Vp | | | | Wn |
| 4 | | Vp | | Un | | |
| 5 | | | Wp | Un | | |
| 6 | | | Wp | | Vn | |

Table 1. Six steps for 120-degree modulation.

In our description, 'step' is synonymous with 'state'. Figure 7 below shows the complete six-step sequence with angles given in units of radians. Figure 7 also shows the current flow as it enters from one coil and exits a second coil.

This current flow corresponds exactly to the six steps of turning the switches on and off. Since each positive phase (U+, V+, and W+) is energized for 120-degree rotation, and each negative phase (U-, V-, and W-) is also energized for 120-degree rotation, this type of modulation is called 120-degree modulation.

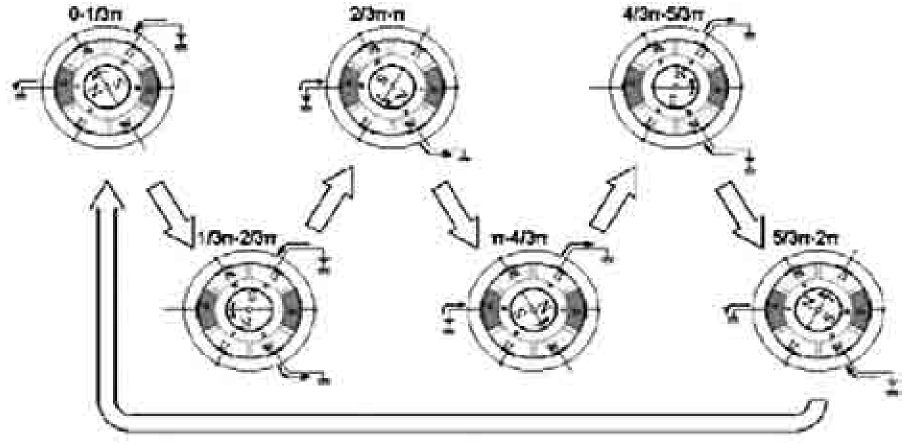

Figure 7. Six step modulation for Brushless DC motor.

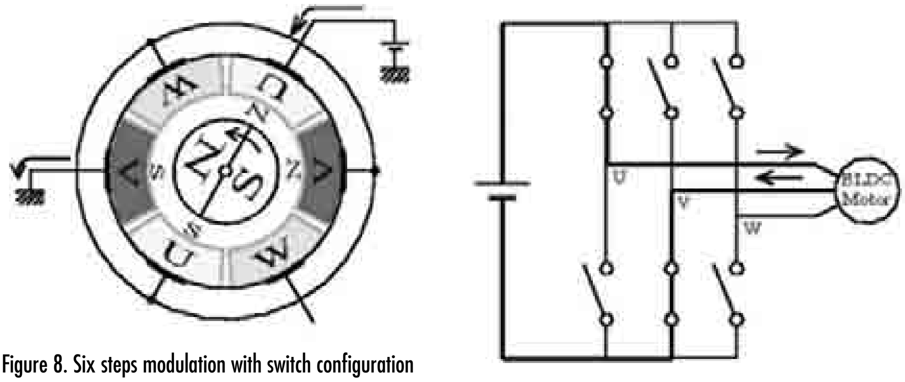

Figure 8. Six steps modulation with switch configuration

At each of six steps, one power-MOSFET or IGBT is switched on or off, hence the term 120degree six-step commutation. Figure 8 above illustrates these principles in a 120-degree drive system.

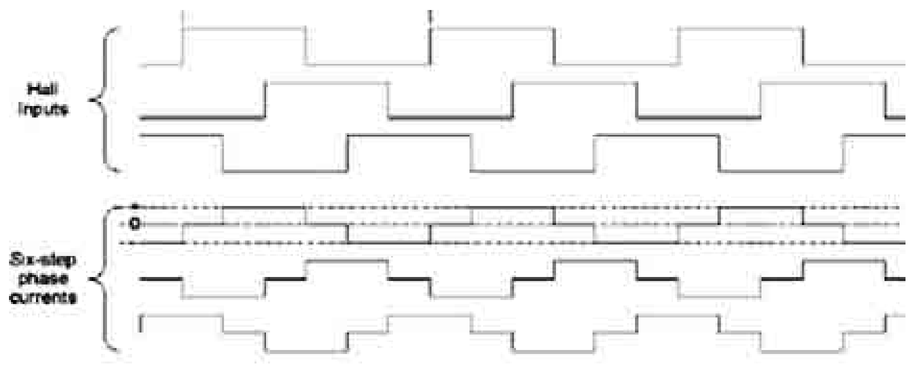

Figure 9. Six step commutation with phase currents behavior.

Typical 6-step commutation (only 2 phase conducting at any time)
This is typical of inverters without 3-phase peripheral and PMSM with Hall Effects.

Control electronics - in particular the MCU - play an important role in this operation. Hall-effect signals are fed into MCU as external interrupts. With every interrupt signal, the MCU performs a state change; in other words, it turns off one switch device and turns on another one. The MCU performs its task by executing interrupt-based code and changing the state of the output pin. The MCU has three interrupt input pins, one for each Hall sensor, and six output pins, one for each switch driver.

The operation of a motor with 120-degree six-step commutation, along with the behavior of the phase currents, is shown in Figure 9, above.

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# FIELD TESTING OF ELECTRIC MOTORS

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## ABSTRACT

This paper addresses electrical testing and inspection of installed electric motors. The main purposes of testing installed electric motors are condition assessment for continued service, or to diagnose suspected faults. The primary focus here will be on electrical testing of three-phase squirrel cage induction motors, however, wound rotor, synchronous and direct current motors will also be dealt with. The emphasis of the paper will be on diagnostic testing and interpretation, as well as physical inspection key points. The tests covered will include insulation resistance, surge, high potential, and measurement of amperes and voltage. Other specialized diagnostic tests that will be addressed include vibration analysis, thermal imaging, and open rotor test. The methodology to combine test results with physical observations to determine condition or assess a fault will be illustrated through the use of case history style examples.

## TESTING OF MOTORS

Routine tests to perform for condition assessment or diagnostic testing of any type of motor, three phase or direct current (DC) include insulation resistance (IR), polarization index (PI) or dielectric absorption (DA), and visual inspection. These tests are all performed with the motor at rest, i.e., offline. Online tests will vary depending on the type of machine, e.g., squirrel cage induction, synchronous, wound rotor, or direct current (DC).

Figure 1: Insulation resistance test of motor stator windings.

The IR test (see Figure 1) is well defined, and applicable to all types of windings. If the winding is random wound (round wire), the PI value may not be meaningful because of the windings capacitive charging time occurring within the first minute or so of applied voltage. For that reason, the DA is more useful, with IR readings taken at 30 seconds and 60 seconds. The PI is most useful with form coil windings, i.e., coils made with rectangular or square wire. If the IR value is greater than 5000 megohms, per IEEE 43, the PI value would not be meaningful and the PI test would therefore not normally be performed.

The scope of the visual inspection will vary with motor enclosure. If there is no access to the motor interior, e.g., removable covers, the inspection will be limited to external surfaces. In that case, items to check include fan covers, cooling fans, terminal box, evidence of cracks in the frame or feet, and broken or missing hardware. The output shaft and coupling or other shaftmounted components should be inspected for evidence of wear or cracks. If the motor enclosure allows access to the interior, a visual inspection can be made of the windings and other accessible internal components, and the air gap between rotor (or armature) and stator (or field poles) can be checked. In addition to visual inspection of the interior a borescope and/or mirrors may be used to probe further into interior components.

## TESTING OF A THREE-PHASE SQUIRREL CAGE INDUCTION MOTOR

If the motor can be operated, routine tests during running, i.e., online, include measuring current for each of the three phases, and line-to-line voltages. Depending on operating conditions, and availability of test equipment, other offline tests include lead-to-lead resistance, hipot, surge test, single phase open rotor test, output shaft runout, alignment of motor to driven equipment, soft-foot check, and lubricating oil sampling for analysis.

The lead-to-lead resistance test can detect high resistance joints in winding and lead connections, and the surge test can detect intra-winding faults. Though manufacturers do not publish tolerances for lead-to-lead resistance, a limit of 5% from the average is typical. Values in excess of that may indicate a high resistance connection. The hipot test should be performed only if the end user is willing to accept the risk of a failure during the test.

The surge test applies a pulse, a decaying sine wave surge, to two parts of the winding and compares the pulses. If the pulses are identical, they appear as a single trace on an oscilloscope display. Any difference in pulses, i.e., a lack of symmetry, results in a display of two traces. That usually indicates a defect or fault. A common issue when surge testing an assembled motor is “rotor coupling”. That is the magnetic interaction between a squirrel cage rotor and the stator winding. During the surge test, this can cause a dual trace to be observed.

Turning the rotor a few mechanical degrees will allow the traces to merge if the winding does not have a fault or other defect, e.g., misconnection.

The single-phase open rotor test is performed with the motor offline. Single-phase power is applied to two of the motor line leads, typically at about 20-25% of rated voltage. The current through the motor leads should be between 50-125% of rated amps. The rotor is manually rotated through a single revolution and the minimum and maximum current are noted. If the difference between minimum and maximum current exceeds a 3% variation, an open rotor is indicated. An open rotor condition exists when a bar, or bars, or end ring connections have become an open circuit. A motor with an open rotor may have lower than normal torque and may exhibit a “beat frequency” vibration often accompanied by an audible beat.

Mechanical tests include the output shaft run out test, which is performed using a dial indicator. The indicator is positioned at the outer surface of the end of the shaft, if possible, or at the shaft adjacent to the coupling and the shaft is rotated. NEMA standard MG1 (hereafter MG1) allows up to 0.003” total indicated runout (TIR) for shafts over 1.625” to 6.500”. Shaft runout beyond the tolerance can cause vibration and could lead to the shaft cracking or breaking.

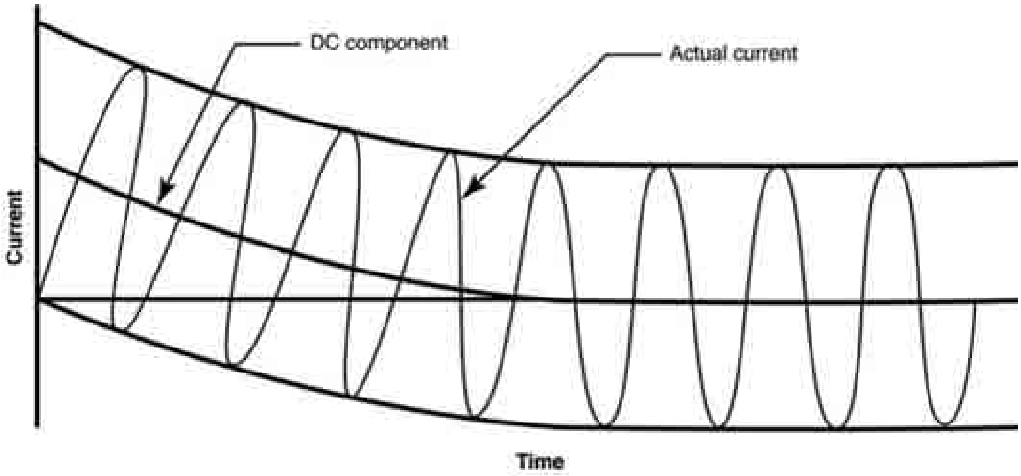

Figure 2: Asymmetrical offset of electric motor inrush current.

| Voltage / HP full load | Minus 10% (414) | | Normal (460) | | Plus 10% (506) | |
|---|---|---|---|---|---|---|
| | Temp. | Efficiency | Temp. | Efficiency | Temp. | Efficiency |
| 10 | 66 | 90.0 | 56 | 91.4 | 55 | 91.5 |
| 20 | 84 | 90.4 | 70 | 91.8 | 67 | 92.1 |
| 50 | 84 | 91.9 | 69 | 93.1 | 62 | 93.6 |
| 100 | 82 | 94.2 | 72 | 94.8 | 69 | 94.9 |
| 200 | 90 | 94.9 | 77 | 95.5 | 74 | 95.7 |

Figure 3: Effect of line voltage variation on temperature and efficiency.

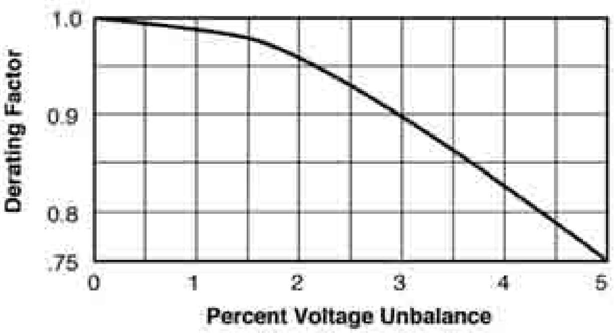

Figure 4: Derating for voltage unbalance per NEMA MG1.

A cause of circuit breaker tripping that has become more prevalent is that due to inrush current during motor starting. A federal law, the Energy Policy Act (EPAct) went into effect in 1992, with many general purpose motors being required to be energy-efficient beginning in 1997. Some of these motors have higher than normal starting current, i.e., locked rotor amps (LRA). That in itself can lead to circuit breaker tripping, however, there is another issue: inrush current. We use the term inrush current to mean the instantaneous current that occurs the moment a motor (or other magnetic device) is energized.

Strictly speaking, inrush is the asymmetrical DC offset that occurs in the first cycle, or few cycles, after being energized (see Figure 2). MG1 states that the inrush current can be 1.8 to 2.8 times the locked rotor current, which is typically 6 to 8 times the full load current. The inrush current may thus be up to 22 (2.8 x 8) times the full load current. The inrush current of a motor that has higher than normal locked rotor current, e.g. energy-efficient motor, can be high enough to cause circuit breaker tripping. Unless the ammeter used to measure the starting current has the capability to measure the momentary inrush (peak) current, it will only indicate the steady-state locked rotor current.

The line-to-line voltages, per MG1, should be within 10% of the rating on the motor. Too high a voltage can increase heating of the magnetic core of the motor; and too low a voltage can reduce the torque developed by the motor (see Figure 3). There is no “rule of thumb” to estimate whether overvoltage will increase or decrease motor current, and likewise with undervoltage.

Another factor related to voltage is unbalanced voltage. MG1 states that the motor should be derated if voltage unbalance exceeds 1% (see Figure 4). This requirement is often confused with the tolerance for voltage variation. Utilities frequently use a 3% voltage balance criteria for the power they supply. According to the MG1 standard, the horsepower derating for a 3% unbalance is about 12%. Derating is not often practical, thus end users may be forced to operate motors with unbalanced voltages. The effect on a motor is reduced output torque, and higher current. The higher current is especially vexing because the current deviates more than voltage.

MG1 states that current unbalance can be expected to be 6-10 times the voltage unbalance.

Applying this rule to the 3% voltage unbalance, the current unbalance could be 18-30%.

Heating is a function of the power loss in a winding, that is, the current squared times the resistance (I2R). With 3% voltage unbalance, the highest current "leg" of the winding may have about 18% more heating due to the associated current unbalance. The additional heating is estimated by taking it as twice the unbalance voltage squared, i.e., 2 x 32 = 18% in this case. An infrared scan of the windings, if accessible, can be used to check the actual temperatures resulting from an unbalanced voltage and current condition.

Infrared thermographic scanning of the motor exterior (see Figure 5) can reveal abnormal heating of parts of the motor, e.g., windings. There are no specific temperature standards for the outer surface of electric motors, i.e., the "skin". Comparing the surface temperatures of identical rated motors with the same or similar load conditions may reveal abnormal heating. If the terminal box cover can be safely removed and the motor energized, an infrared temperature measurement of the visible stator core can be made. The temperature at the axial center of the core is typically within 5°C of the winding temperature. That temperature can indicate an overheated winding. For example, a Class B insulated motor winding should have a temperature of not more than 120°C, and the temperature at the core surface should not exceed 115°C.

Figure 5: Infrared thermographic image of a synchronous motor.

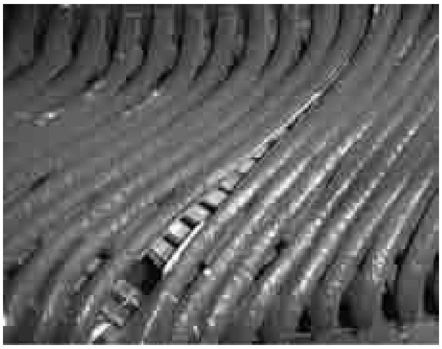

Figure 6: Stator coil damaged by short-circuit or inrush current.

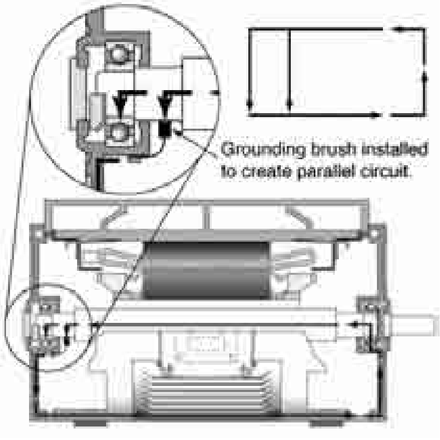

Figure 7: Shaft current paths through electric motor.

If the interior of the motor is accessible, visual inspection for defects or damage, such as to winding coil bracing (see Figure 6), can be made. Mirrors on extension rods can be used to further probe the interior. Borescopes can probe even further than mirrors, and may allow inspection of the rotor interior, and between the stator core and frame. Inspection of the rotor interior may reveal debris or other contamination, loose fit of the rotor core to shaft, or possibly cracked welds. Likewise, inspection between stator and frame may reveal debris or other contamination, cracked welds and possibly blocked ventilation ducts.

Large motors and motors supplied by variable frequency drives (VFDs) should be checked for the possibility of shaft currents (see Figure 7), even if none are suspected. Large motors may have shaft currents induced due to dissymmetry in the magnetic circuit, e.g., due to segmented laminations. VFDs may cause capacitive currents to link the rotor and stator through the bearings. The bearings will fail prematurely due to degradation from the consequential circulating "shaft" current. Measuring the current directly is not practical, as that would require a current transformer be wrapped around the shaft inside the motor, i.e., between bearings. The alternative is to measure the voltage from frame to shaft to determine if the voltage magnitude is great enough to indicate the possibility of damaging shaft currents.

One method for measuring shaft voltage is to attach a true RMS voltmeter lead to the frame and the other lead to the shaft by some type of brush-like device. The shaft connector can be a #2 pencil with part of its tip near the eraser cut away to allow the meter lead to contact the graphite "lead". The pencil point drags the shaft and senses voltage. Use of the meter lead to directly sense voltage is not recommended because it is typically not a continuous contact. If the sensed voltage is greater than 100 millivolts AC for rolling bearings or over 200 millivolts AC for sleeve bearings, damaging shaft currents are probably present. Another criteria is given in MG1, stating that a shaft voltage in excess of 300 millivolts AC measured from the shaft at the opposite drive end to the shaft at the drive end indicates damaging shaft currents may exist.

Figure 8: Synchronous motor rotor.

## TESTING OF A THREE-PHASE SYNCHRONOUS MOTOR

The previously mentioned tests that apply to a three-phase squirrel cage induction motor also apply to the synchronous motor. Additional offline tests that apply to a slip-ring type synchronous motor with an accessible interior include drop test of rotating field coils (in lieu of surge test), air gap measurement, brush spring tension, brush wear, and collector ring condition and runout. If the synchronous motor has brushless excitation, the diode rectifier assembly and other electronic components should be tested for conduction, shorts and open circuits. It is important that electronic components be electrically isolated from windings that are under electrical test. The winding test voltages may be beyond the insulation rating of some electronic components.

If equipped with a brush-type exciter, the fields and armature should have the offline routine tests performed. Online tests include field voltage and current, and armature voltage and current. During operation, other online tests that can be performed on a synchronous motor include measuring rotor current and voltage and, if possible, stator winding power factor.

The voltage drop method can be used to test the synchronous motor rotor (see Figure 8) for shorted coils. The method consists of applying 120 volts AC to the rotor coils, which are usually connected in series. The voltage drop across each coil should be within 10% of the average coil test voltage. The reason for using AC instead of DC for the drop test is that DC is not as sensitive to detecting shorted turns. For example, a coil with 4 of 100 turns shorted would have a resistance and DC voltage drop about 4% below normal, a value within the typical acceptance tolerance of 5%. However, with AC applied, the 4 shorted turns act as a 4 turn autotransformer secondary, and the magnetic coupling to the 96 unshorted turns results in a large circulating current in the shorted turns. That causes the AC voltage drop across the coil to become excessive. A shorted coil typically far exceeds the 10% maximum variation tolerance of the AC voltage drop test.

A synchronous motor with collector rings must not be started with the rotor circuit open.

If the rotor circuit is open, it behaves as the secondary of a transformer, with many turns, and the stator winding is the primary. The result can be thousands of volts developed in the rotor winding circuit, and a high probability of insulation breakdown to ground.

One of the more common problems associated with a synchronous motor is that it will not pull into synchronism. The synchronous motor has a squirrel cage winding, termed an amortisseur winding, which is used to start the motor. If there is an open circuit in the amortisseur winding, or if load torque is excessive, the rotor will not attain near-synchronous speed. The speed required is typically about 95-97% of synchronous speed for the controls to successfully apply DC excitation to the rotor coils and have the motor "pull in" to synchronism.

The synchronous motor squirrel cage winding can be tested for open circuits using the same technique as for a squirrel cage rotor; however, the main rotor circuit must be shorted on itself to prevent developing a high voltage within it when the stator is energized. Assessing the actual load condition is difficult, and it is usually more practical to deliberately reduce the load if possible and determine the load point at which the motor will successfully pull into synchronism.

### TESTING OF A THREE PHASE WOUND ROTOR MOTOR

In addition to the routine tests also applying to a wound rotor, many of the slip-ring type synchronous motor tests also apply. The offline tests are predominantly mechanical, including brush spring tension, brush wear, and collector ring condition and ring runout. Operational tests include current in each phase and open circuit rotor voltage ("ring-to-ring"). The output frequency of the rotor at full speed is usually only a few Hertz, possibly requiring special metering to measure phase current. If a fault is suspected in the rotor winding, an electrical test that can be performed is the rotor open circuit voltage test.

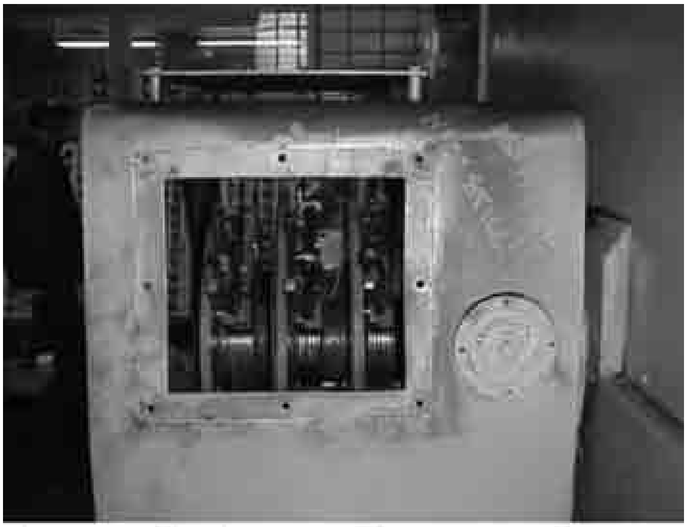

Figure 9: Slip ring assembly cover can be removed to access rings for open circuit rotor test.

The open circuit rotor test (see Figure 9) is done with the motor uncoupled from the load.

The stator is energized, with reduced voltage if possible for safety, or with full rated voltage if that is all that is available. The rotor is mechanically uncoupled for this test and should not rotate, though it may "crawl". If the rotor is shorted it will try to accelerate to full speed, thus a short in the rotor can be detected by this test. If the rotor does not rotate, i.e., it is not shorted, the ring to ring voltage can be measured. The ring-to-ring voltage with rated voltage applied to the stator should be within about 5% of the nameplate rotor voltage rating. If reduced voltage is applied to the stator for this test, the rotor voltage will be lower in direct proportion to the stator voltage, that is, the rotor and stator windings act as secondary and primary transformer windings, respectively.

### TESTING OF A DIRECT CURRENT (DC) MOTOR

The fields and armature of a DC motor should have the offline routine tests performed. Other offline tests include drop testing of field coils, including shunt, series interpoles and compensating windings, as applicable. Also, inspect the commutator condition, brush spring tension, brush wear, commutator runout, brush fit in brushboxes, and brushholder neutral setting.

Lead markings should be noted, e.g., lead S1 connected to A2, etc. Online tests of the DC motor include field voltage and current, armature voltage and current, and speed.

Drop testing of fields can be done using the same technique as for synchronous rotor poles, i.e., apply AC voltage and measure the voltage drop across each coil. The shunt field circuit can be tested with 120 volts, and the series and interpole circuits with a lower voltage, typically about 30 volts. The same 10% variation from average applies as an acceptance tolerance. It is usually not possible to access the internal connections, therefore, the commutator side end bracket may need to be removed for drop testing.

The brush neutral is tested by applying about 120 volts

AC to the shunt field leads and measuring the induced voltage at adjacent brushholder arms. Make certain that the shunt field leads and armature leads are isolated from the drive or other power source. The induced voltage at the brushholders should be below 10 millivolts AC. If it is not, adjust the brushholder assembly rocker ring by rotating it in the direction that reduces the induced voltage, until the voltage is below 10 millivolts. If the motor can be operated uncoupled and test run in each direction, i.e., clockwise and counterclockwise, the neutral can be checked by comparing no load speeds. With the exact same shunt field current and armature voltage applied, the no load speeds in each direction should be within 1%. Further, there should be no visible sparking at the brushes.

## CASE HISTORIES:

### MOTOR RUNNING HOT

A 250 horsepower motor rated 276 amperes at 460 volts is reportedly running hot and drawing unbalanced currents. The currents are 243, 256 and 299 amperes, with line voltages of 478, 485 and 495 volts. The surface temperature of the motor, which has a 1.15 service factor, was measured near the nameplate and was 192 degrees F (89°C). The windings are Class B (130°C) and the maximum ambient rating is 40°C. The determination to be made is whether the motor is operating at too high a temperature, and if so, how it can be corrected.

The voltage unbalance should be checked to determine if is it within the MG1 1% tolerance for operation without derating. The average of the 478, 485 and 495 volt values is 486 volts, and the maximum deviation from the average is 9 volts (495 – 486). The voltage unbalance is 9/486, or 1.9%. Although MG1 does not have a limit for current deviation, the average of the 243, 256 and 299 ampere currents is 266, the maximum current deviation is 33 (299 – 266) amperes, and the current deviation 33/266 or 12.4%. The MG1 standard states that current unbalance is typically 6 to 10 times the percent voltage unbalance. In this case, the current unbalance of 12.4% is about 6.5 times the voltage unbalance of 1.9%, a value that conforms to the MG1 expected value tolerance. The voltage unbalance is the probable cause of the current unbalance.

The voltage unbalance is almost 2%, and according to MG1 (see Figure 4), the motor should be derated to about 88% load. The insulation class, service factor and ambient rating allow a winding temperature rise of 90°C per MG1. However, the 90°C rise rating is based on the motor being at service factor load. At 1.0 service factor the temperature rise limit would be 80°C. It is not advisable to continuously operate a motor in the service factor range, i.e., above its normal rating, therefore the 80°C limit would be more reasonable than the 90°C value. The total temperature of the winding with a 40 degree ambient and 80°C rise is (80 + 40) 120°C.

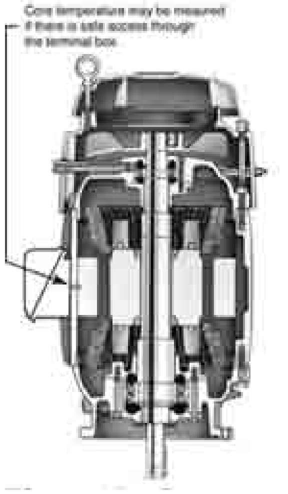

Figure 10: Core temperature may be measured if there is safe access through the terminal box.

The 89°C surface temperature measurement for this example does not exceed 120°C, thus it does not indicate an overtemperature condition. However, it does not indicate an acceptable temperature since there is no applicable standard. If the stator core can be safely accessed through the terminal box, the core temperature could be measured (see Figure 10). If the terminal box is centered with respect to the axial length of the core, the surface temperature of the core in the terminal box is typically within 5°C of the winding temperature. In this example we will assume that the core measurement through the terminal box could be made, and the core surface temperature was 118°C. Adding the potential temperature differential of 5°C, the winding would be about 123°C. That value exceeds the 120°C limit, indicating that the winding is probably operating in an overtemperature condition.

The current in one of the phases was 299 amperes, versus 276 rated. Heating is a function of I2R power losses and the high current phase will have (299/276)2, or 1.18 times greater heating than normal. That is another indicator that the winding is probably overheated and corrective action is needed. Derating the motor is often not practical, and would not address the root cause of the problem, which are the unbalanced voltages. One possible solution would be to have the utility adjust supply transformer taps to improve voltage balance if it applies to the entire facility. Another alternative would be to add a buck-boost autotransformer to adjust the motor supply voltage balance. If variable speed operation would be desirable, applying a VFD would provide a balanced voltage supply to the motor, although the VFD may need to be oversized to accommodate the higher currents in one or more of the unbalanced utility supply phases.

### MOTOR WILL NOT START HIGH INERTIA LOAD

A call is received in the middle of the night that a motor rated 1250 horsepower, 4000 volts, 158 amperes, 3555 rpm will not come up to speed. Upon arrival, after a few questions are asked, it is learned that the motor has been installed as a replacement for a motor removed for reconditioning. Two possible causes for the motor startup problem come to mind, an open rotor or load inertia in excess of the motor capability. An open rotor, e.g., a broken bar or bars, can reduce starting and running torque. A high inertia load may require more torque than the motor can produce during startup, at one or more points in the motor speed-torque curve. The motor may have enough torque to drive the load at rated speed, but not enough starting torque to bring the load, e.g., a large fan wheel, up to speed.

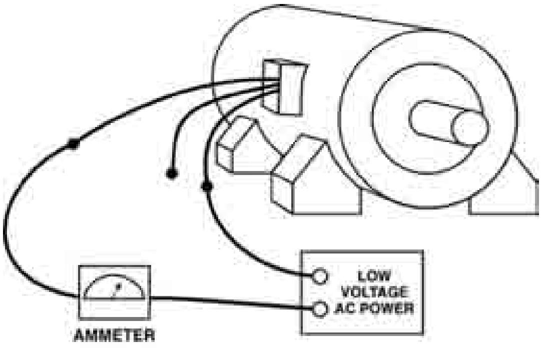

Figure 11: Single phase open rotor test.

Since the motor will not operate under load, the rotor testing will be a single-phase open rotor test at standstill. The test is performed by applying about 480 volts to 2 of the 3 motor

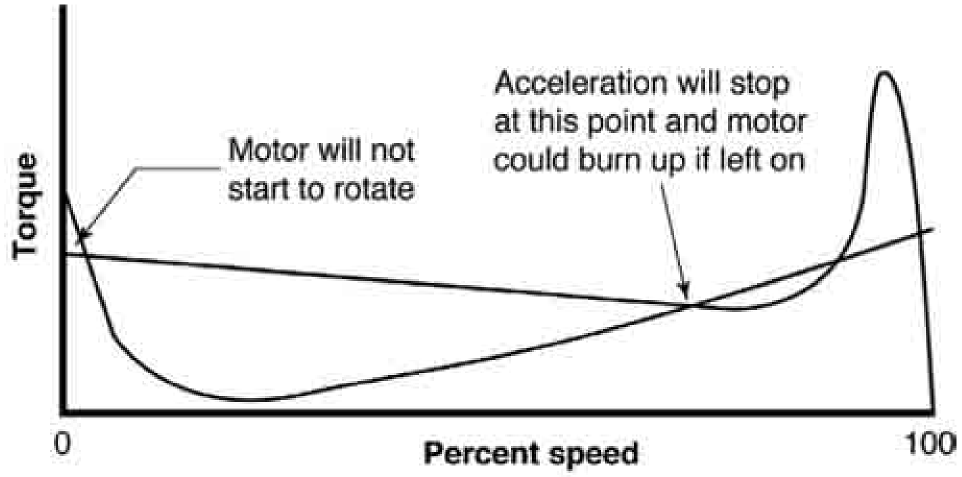

Figure 12: Effect of load inertia on motor starting.

line leads (see Figure 11), and manually rotating the shaft while monitoring current. In this case, the test current varied slightly, from 90 to about 90.5 amperes. The current variation was only .5/90, or about 0.5%, well within the 3% acceptable value mentioned earlier. When performing this test, if the rotor is open, in addition to the current variation, there is typically a change in torque that can be detected when manually rotating the shaft. It is also common to hear a change in sound as the test current varies due to an open rotor.

The possibility of excessive load inertia is the other high probability cause of the motor not accelerating to rated speed. This situation occurs when the load torque exceeds the available motor torque at some or all points in the motor speed-torque curve (see Figure 12). If the load torque always exceeds the motor torque, the rotor will not turn and the motor will be in a stalled state until protective devices take it off line. In other cases, the rotor accelerates until it reaches a point at which the load torque is greater than motor torque, and the rotor continues to rotate at that speed. The current remains essentially locked rotor, causing rapid heating until the protective devices take the motor off line. In both cases of inadequate torque, the protective devices may not de-energize the motor until after the stator or rotor, or both, have been damaged.

There is no simple means to determine the load inertia by test; it is usually necessary to consult the driven equipment manufacturer for the load inertia rating, termed WK2. Also, check with the motor manufacturer for the actual inertia capability of a specific motor, particularly if it has difficulty accelerating a load.

Another factor in motor output torque is applied line voltage. If the motor is started using reduced voltage (e.g., an autotransformer), or reduced torque method (e.g., wye-delta), the starting torque will be significantly reduced. Also, check the actual line voltage at the motor terminals at starting. Motor output torque varies as the square of applied voltage, for example, at 80% voltage the torque is only about (.8 x .8) 64% of normal. Some applications may allow a reduction in the load on the motor at startup. If that is possible, consider reducing load to determine the point at which the motor can accelerate the load. This information can be useful in quantifying the magnitude of the starting problem. For example, if the load is reduced 5% and the motor starts, increasing the supply voltage may eliminate the problem.

# SENSORLESS STATOR WINDING TEMPERATURE ESTIMATION FOR INDUCTION MACHINES

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## INTRODUCTION

Three-phase induction machines are used extensively in modern industry due to their cost effectiveness, ruggedness and low maintenance requirements. A single industrial facility may have thousands of induction motors operating along its assembly lines. As a result of this coordinated operation, malfunction of an induction motor may incur financial losses not only associated with the individual motor's repair or replacement, but also losses associated with the down time of the entire assembly line and the loss of productivity. For this reason, reliable motor operation is crucial in many industrial processes. To ensure reliable motor operation, protection devices, such as thermal relays, are widely used in modern industry. Condition monitoring of induction machines, the underlying technology in motor protective devices, has experienced rapid growth in recent years.

A major task of induction machine condition monitoring is to provide accurate and reliable overload protection for motors. According to IEEE Industry Applications Society (IAS) and Electric Power Research Institute (EPRI) surveys, 35–40% of motor failures are related to the stator winding insulation and iron core [1]-[3]. These failures are primarily caused by severe operating conditions, such as cyclic overload operation; or harsh operating environments, such as those in the mining or petrochemical industries [4]. Although induction motors are rugged and reliable, the stator winding insulation failure is potentially destructive. It often leads to stator winding burnout and even total motor failure. Protection of the stator winding from insulation failure is the main theme of this work.

### 1.1 STATOR WINDING INSULATION FAILURE

The organic material used for insulation in stator windings of an induction motor must work below a certain temperature limit. Operating above this temperature limit for short durations does not seriously affect the life of the motor, but prolonged operations beyond the permissible temperature limit will produce accelerated and irreversible deterioration of the stator winding insulation material. Such deterioration often expedites the motor's aging process and eventually reduces the motor's life. As a rule of thumb, the motor's life is reduced by 50% for every 10°C increase above the stator winding temperature limit.

Since excessive thermal stress is identified from industry practice as the primary cause of stator winding insulation degradation, especially for small-size mains-fed induction machines, the National Electrical Manufacturers Association (NEMA) has established permissible temperature limits for the stator windings of an induction machine based on its insulation class to ensure its continuous and reliable operation. Typical temperature limits for the stator windings are given in Table 1.1 [5].

There are several conditions under which the temperature limit can be exceeded, resulting in acceleration of stator winding insulation degradation: transient overloads, running overloads and abnormal cooling conditions [4]-[6].

Transient overloads and running overloads are related to two regions of motor operation [6]. The first region of motor operation is the transient overloads with 250 to 1000% full-load current. These overloads include motor starting, wherein the motor draws up to 6 times its rated current during acceleration; motor stall, wherein the motor fails to accelerate the load to the desired speed during its starting phase; and motor jam, wherein the motor is stopped during its normal operation due to a sudden mechanical lock. In each of these scenarios, a significant amount of heat is generated by the large amount of inrush current in the stator winding due to the stator $I^2R$ loss. The lack of ventilation, caused by the slow or even complete halt of rotor movement, makes it difficult for the heat to be dissipated [7]. Therefore, the transient overloads can be regarded as adiabatic processes with very fast thermal transients. Normally it takes between 25 to 30 seconds for a typical motor stator winding to reach 140°C rise above its ambient temperature during a locked rotor condition [6].

In most applications, general and special-purpose NEMA T-frame motors may be considered to be protected at transient overloads when NEMA Class 20 overload relays are used. These relays allow 6 times full-load current to pass through the motor for 20 seconds [8].

The second region of motor operation is the running overload with 1 to 2 times the full load current. In this region the motor is continuously running, thereby providing a certain degree of heat dissipation for the internal losses, and resulting in a gradual

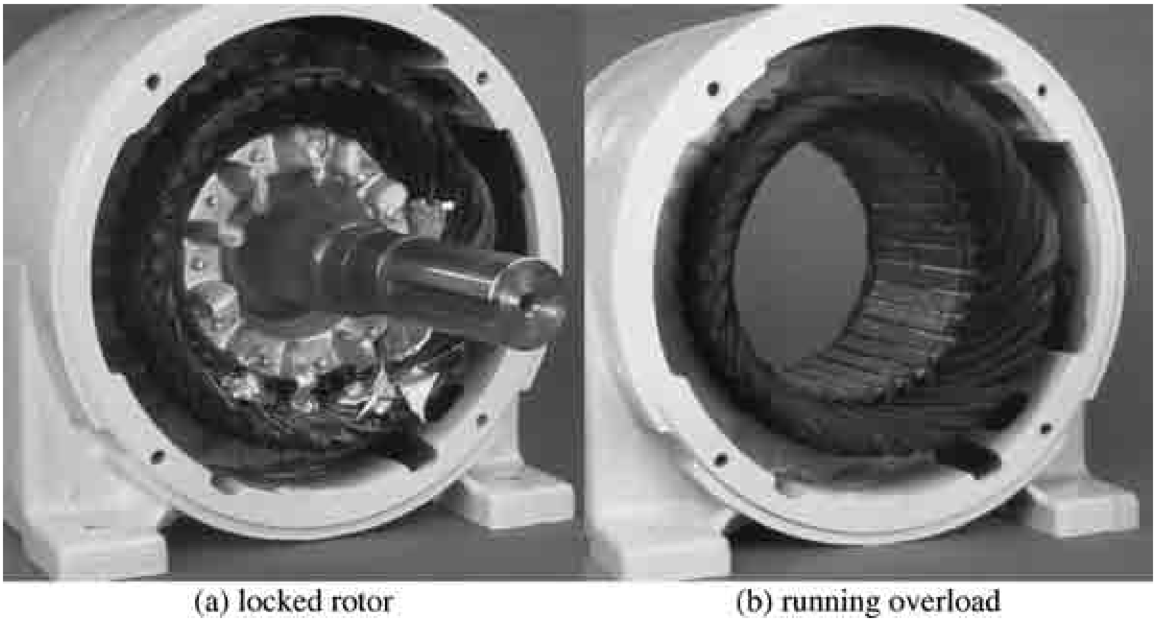
| Insulation Class | Ambient Temperature (°C) | Rated Temperature Rise (°C) | Hot Spot Allowance (°C) | Hot Spot Temperature (°C) |
|---|---|---|---|---|
| A | 40 | 60 | 5 | 105 |
| B | 40 | 80 | 10 | 130 |
| F | 40 | 105 | 10 | 155 |
| H | 40 | 125 | 15 | 180 |

Table 1.1: Temperature limits for different insulation classes

increase of the stator winding temperature.

Unlike the motor operation in transient overloads, the internal heat is transferred to the motor ambient by means of conduction and convection during running overloads. Therefore, the thermal time constant under this type of motor operation is far larger than that under the transient overloads. This thermal time constant is determined by a number of factors, such as the motor design, the rotor speed and the temperature of the surrounding air. As a result, while a definite time relay can be used to protect the motor from transient overloads, a more sophisticated scheme is needed to protect the motor from running overloads. This defines the scope of the research presented in this work.

Abnormal cooling conditions are another possible cause of stator winding temperature rising beyond its limit. Typically, the cooling ability of a motor is reduced due to a defect or fault in any of the components in the motor's cooling system. This often leads to an abnormal motor temperature rise. For instance, when the fins or casing of the motor is clogged with dust or other particles, transfer of motor internal heat to its ambient is obstructed and, as a result, the motor temperature increases. Another example is when the cooling of the motor is compromised due to high ambient temperature. Standard motors are designed to operate at an ambient temperature below 40°C, therefore the insulation life decreases significantly as the motor ambient temperature increases. There are even more serious situations in motor cooling, caused either by a broken cooling fan or accidentally blocked air vents or ducts. All of them decrease the motor's cooling ability and lead to possible motor failure.



(a) locked rotor (b) running overload

Figure 1.1: Stator winding damage [Courtesy of Electrical Apparatus Service Association (EASA) Inc., St. Louis, USA].

Two examples of the damage in the stator winding due to excessive thermal stress are shown in Figure 1.1. Figure 1.1(a) shows the damage in the stator and rotor caused by a locked rotor condition, which is one type of transient overloads. Figure 1.1(b) shows the stator insulation damage due to excessive motor running overloads.

## 1.2 TEMPERATURE MONITORING

To safeguard the stator winding from insulation failure and extend the motor life, the stator winding temperature must be continuously monitored. Whenever the stator winding temperature exceeds the permissible limit, the motor should be shut down to avoid damage to its stator winding insulation materials. Many techniques have been developed for induction motor protection under overload conditions to guarantee reliable motor operation. These techniques can be classified into 3 major categories:

1) Direct temperature measurement
2) Thermal model-based temperature estimation
3) Parameter-based temperature estimation

Direct temperature measurement of the stator winding temperature is performed using embedded thermocouples, thermally sensitive resistors (thermistors), resistive temperature detectors (RTDs) or infrared cameras [9]. Such thermal sensors are capable of providing reliable temperature readings at their installed locations. However, since most thermal stresses lead to localized failures inside the stator winding, where these thermal sensors are not installed, the direct temperature measurement may not provide complete overload protection for the whole stator winding. In addition, direct temperature measurement is only considered a cost-effective method for large machines. The installation of thermal sensors in small machines is extremely difficult and costly.

Thermal model-based temperature estimation is the most commonly used technique in motor overload protection. Dual-element time-delay fuses, eutectic alloy overload relays and microprocessor-based motor protective relays are 3 major types of protective devices based on the thermal models of induction machines.

The dual-element time-delay fuse, which is the most extensively used device for motor overload protection due to its low cost, consists of a short-circuit element and an overload element [8]. A properly sized dual-element time-delay fuse can provide protection for both short-circuit and running overload conditions. However, each time the motor is overloaded, the fuse needs to be replaced.

The eutectic alloy overload relays are another type of motor protective relay based on the emulation of the thermal characteristics of the stator winding. When coordinated with the proper short-circuit protection, this type of overload relay is intended to protect the motor against overheating due to excessive overcurrents. Nevertheless, the thermal discrepancy between the eutectic alloy overload relays and the motors makes it difficult to match both heating and cooling characteristics of the motor under all thermal conditions. As a result, the device often trips the motor based on an approximate estimate of the stator winding temperature, and spurious trips are common with these devices [10].

Among all devices using thermal model-based temperature estimation techniques, the microprocessor-based motor protective relays represent the state-of-the-art in motor protection [6]. To provide an estimate of the motor's stator winding temperature, the microprocessor-based overload relay first calculates the power losses from the current measurements at motor terminals based on the induction motor equivalent circuit. The relay then derives the stator winding temperature from a thermal model for the induction motor.

Thermal model-based temperature estimation provides an accurate and reliable temperature estimate when compared to fuses or eutectic alloy overload relays, thus ensuring complete motor overload protection. In addition, it can be adjusted easily for different classes of motors due to its flexible software-based algorithm. However, similar to fuses and eutectic alloy overload relays, it cannot respond to changes in the cooling capability of a motor, which are often caused by either a clogged motor casing or a broken ventilation fan.

Parameter-based temperature estimation technique presents an alternative method in estimating the stator winding temperature. Since resistance is a direct indicator of temperature, this type of method provides superior performance over the thermal model-based temperature estimation. Besides the high accuracy associated with the estimated stator winding temperature in this method, it is capable of responding to the changes in the motor cooling condition because the temperature variation is reflected immediately on the stator resistance estimate. Compared with the direct temperature measurements from either thermocouples or RTDs, this method requires no temperature detectors, and is therefore non-intrusive in nature and inexpensive.

Reference [11] presents a detailed method of calculating the stator resistance, $R_s$, and the rotor resistance, $R_r$, from the induction machine equivalent circuit. However, as indicated in [12], a direct estimate of stator resistance at high speed operation is extremely difficult and susceptible to parametric errors from rotor resistance and motor inductances.

To avoid the large error in the estimated stator resistance, one method assumes a fixed ratio between $R_s$ and $R_r$ [13]. Since Rr is strongly dependent on the rotor frequency due to skin effect, while $R_s$ is uncorrelated to rotor frequency, the stator resistance estimate obtained in this manner is not the 'true' stator resistance, and consequently it is not a direct indicator of stator temperature. Other researchers propose DC injection method for line-connected and soft-started induction machines for parameter-based temperature estimation [14]-[16]. However, the major problem with using DC injection for $R_s$ estimation is the torque pulsation and the negative torque induced by the DC current component [15].

In addition to the aforementioned variety of devices used for overload protection, bimetallic thermal protectors are also a popular type of temperature monitoring device. They are typically used on fractional to small integral-horsepower (up to 5 hp) AC induction motors to provide built-in overheating protection.

Detecting abnormal cooling conditions during motor operation is also one important aspect of induction machine temperature monitoring. In case of a cooling system fault, the motor may operate at a higher temperature under the same load or thermal condition compared to when the cooling system is healthy. This results in accelerated stator winding insulation degradation.

In references [17]-[18], methods for detecting abnormal cooling situations are proposed. By comparing the difference in temperature estimated from the thermal model and the temperature estimated from the resistance, the motor cooling system is monitored. If the difference is beyond a predetermined threshold value, a fault signal is generated to indicate a malfunction in the motor's cooling system. The implementation of this scheme requires complete knowledge of the motor electrical and thermal models. Sophisticated signal processing techniques are necessary to unify these two models and produce a reliable estimate.

### 1.3 PROBLEM STATEMENT

It was shown in the previous sections that temperature monitoring of the stator winding is crucial to protecting not only an individual motor but also the whole industrial process driven by motors. This work focuses on the development and implementation of a fast, efficient and reliable algorithm to estimate the stator winding temperature online with only voltage and current measurements from the terminals of small to medium size mains-fed induction machines. In addition, motor cooling system condition monitoring is also explored for complete stator winding protection. The ultimate goal of this work is to provide a comprehensive set of algorithms for motor overload protection to the next generation microprocessor-based protective relays.

The development of a thermal monitoring tool begins with a thorough investigation of state-of-the-art techniques for stator temperature estimation. The thermal model-based temperature estimation technique, though simple and reliable, suffers from inaccuracies in the thermal model parameters. These inaccuracies often lead to conservative estimates of stator winding temperature, resulting in spurious trips and unnecessary interruption of the whole manufacturing process. On the other hand, the parameter-based temperature estimation technique, though accurate, is highly susceptible to the errors in the induction machine electrical parameters.

Theoretically, estimation of $R_s$ using the negative or zero sequence model is insensitive to motor parameter errors; however, continuous monitoring of $R_s$ in practice is virtually impossible since small negative sequence or zero sequence current often causes singularity problems in signal processing. If the negative or zero sequence currents are intentionally injected into the machine to obtain an estimate of $R_s$, the inherent motor asymmetry in different phases may also cause large errors in the $R_s$ estimate. Other problems associated with the current injection method include the deterioration of motor performance due to torque pulsations and motor internal heating. For example, the DC injection technique proposed in references [15]-[16] usually introduces undesired torque pulsations and motor performance deterioration.

Based on the analysis of the pros and cons of both the thermal model-based temperature estimation techniques and the parameter-based techniques, a new method is suggested in this proposal. First, a hybrid thermal model (HTM) is proposed to correlate the stator temperature with the rotor temperature. This model also accounts for the disparities in thermal operating conditions for different motors of the same rating. Then the rotor temperature, obtained from the rotor resistance estimation, is regarded as an indicator of the motor's thermal characteristics. The rotor temperature is used to tune the parameters in the HTM to reflect the specific motor's cooling capability. Finally the HTM is run independently after the tuning process to provide an accurate and reliable estimate of the stator winding temperature.

An abnormal cooling condition in motor operation, such as a clogged motor casing or a broken ventilation fan is also considered in this work. The entire algorithm is fast, efficient and reliable, making it suitable for implementation in real time for protection purposes.

## SUMMARY OF PREVIOUS WORK ON STATOR TEMPERATURE ESTIMATION

The temperature rise inside an induction machine is caused by the accumulation of heat on both the stator and the rotor. The heat is produced from the motor losses. The motor losses are made up of following losses [19]:

- Losses dependent on the motor current
  - o Stator $I^2R$ loss
  - o Rotor $I^2R$ loss
  - o Stray-load loss
- Losses independent of the motor current
  - o Core loss due to eddy current and hysteresis
  - o Friction and windage loss

During the conversion from electrical energy to mechanical energy by the induction machine, these losses are generated inside the machine and are dissipated in the form of heat by means of conduction and convection. For most modern small-size mains-fed induction machines, the major portion of the heat comes from the $I^2R$ losses.

A complete overload protection scheme needs to provide protection to the induction machine at all times [20]. However, the thermal characteristics of an induction machine during its starting phase are vastly different from that during the running phase. Therefore, a good stator winding temperature estimator should be able to distinguish between these two different motor operating modes and adjust the temperature estimator accordingly.

There are currently two major types of stator winding temperature estimation techniques available: the thermal model-based temperature estimation technique and the parameter-based temperature estimation technique. Their basic concepts are summarized and evaluated here. In addition, a comparison is made between these two types of techniques.

### 2.1 TEMPERATURE ESTIMATION BASED ON THERMAL MODELS

Thermal limit curves are typically used to provide knowledge of the safe operating time for an induction machine under locked rotor conditions, acceleration condition and running overload conditions [21]. The thermal model-based temperature estimation techniques normally emulate the thermal limit curves to achieve complete motor overload protection. Figure 2.1 shows the typical thermal limit curves for an induction machine. To insure proper motor operation, the protective devices must trip the motor once it goes beyond its normal starting or running condition and reaches its thermal limits.

Both the dual-element time-delay fuses and the microprocessor-based overload relays simulate the motor internal heating based on the given thermal limit curves.

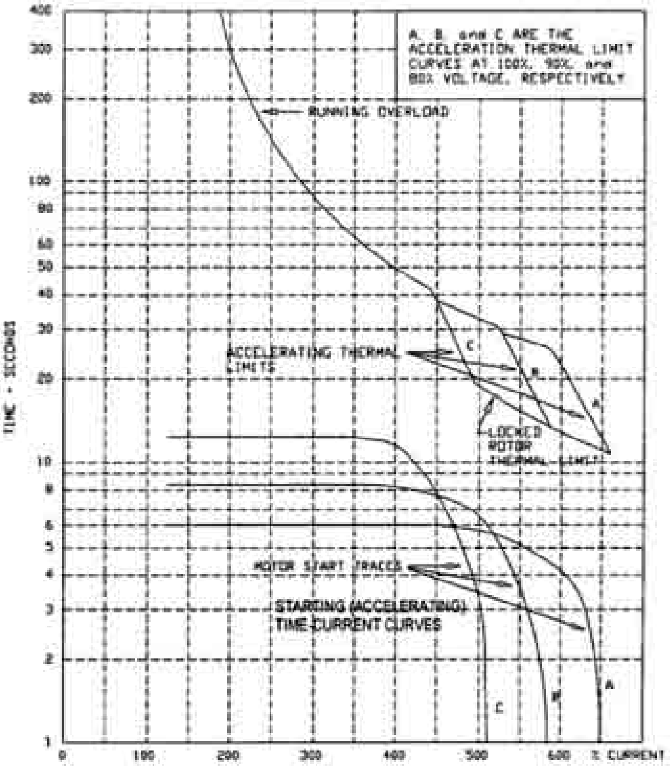


Figure 2.1: Typical thermal limit curves from reference [21].

### 2.1.1 DUAL-ELEMENT TIME-DELAY FUSES

Dual-element time-delay fuses consist of a short-circuit element and an overload element, as shown in Figure 2.2, providing complete protection to the motor at both the starting phase and the running phase.

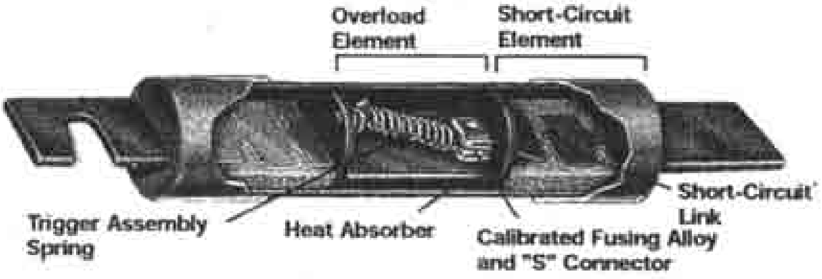
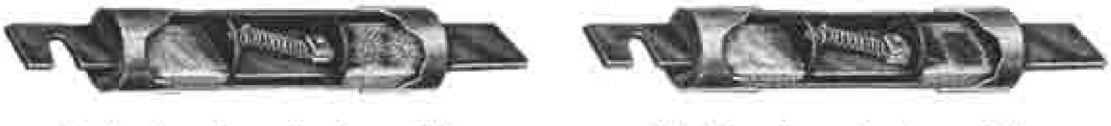


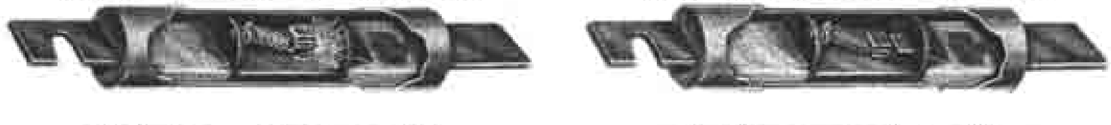
Figure 2.2: The structure of a dual-element time-delay fuse from reference [8].

As shown in Figure 2.3(a), when a short circuit occurs in the induction machine, the inrush current causes the restricted portion in the short-circuit element to melt. After the arc is suppressed by the arc quenching material and the increased arc resistance, a gap is produced inside the short-circuit element of the fuse, indicated by Figure 2.3(b). The power supply is therefore cut off from the motor. Under sustained overload condition, the trigger spring fractures the calibrated fusing alloy and releases the connector in Figure 2.3(c). The release of the connector produces a break inside the overload element of the fuse, as illustrated in Figure 2.3(d).

Figure 2.4 shows the time-current diagram for a properly sized dual-element time-delay fuse in protecting a motor. The thermal limit curve emulated by the fuse lies on the right side of the normal motor starting and running condition, therefore, the motor is protected at both the starting phase and the running phase.



(a) During short-circuit condition (b) After short-circuit condition



(c) During overload condition (d) After overload condition

Figure 2.3: Dual-element fuse operating mechanisms under different conditions [8].

The dual-element time-delay fuse is not only suitable for standalone motor overload protection, but also an economical means in providing backup protection to an overload relay. It is inexpensive and virtually free from maintenance. However, this type of device trips the motor based only on a crude estimate of the stator winding temperature and is subject to spurious trips as well as under-protection [6], [10].

### 2.1.2 THERMAL MODELS WITH A SINGLE TIME CONSTANT

Most microprocessor-based motor overload protective relays, representing the state-of-the-art in motor protection, rely on the motor heat transfer models to predict the stator winding temperature. Thermal models with a single thermal capacitor and a single thermal resistor are widely adopted in the industry. The thermal capacitance and thermal resistance are normally predetermined by a set of parameters for a given class of motors, classified by their full load current (FLC), service factor (SF) and trip class (TC) according to reference [22].

Thermal models with a single thermal capacitor and a single thermal resistor are derived from the heat transfer of a uniform object, as shown in Figure 2.5,

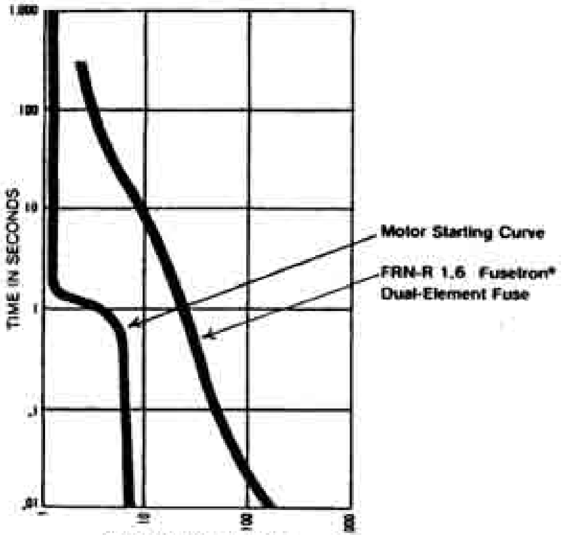


Figure 2.4: Motor starting and running curves and the dual-element time-delay fuse thermal limit curve [8].

The quantities, $\theta$ and $\theta_A$ , in *°C*, are temperatures of the uniform object and its ambient, respectively. The power input into this uniform object is determined by the power losses from the current, *I* (unit: *A*), on the resistor, *R* (unit: $\Omega$ ). Heat is dissipated through the boundary of the uniform object (the shaded region in Figure 2.5) to the ambient. The thermal resistance, $R_{th}$, in °C/W, models this heat transfer. The thermal capacitance, $C_{th}$, in *J*/°C, is defined to be the energy needed to elevate temperature by one degree Celsius for the object. It represents the total thermal capacity of the object.

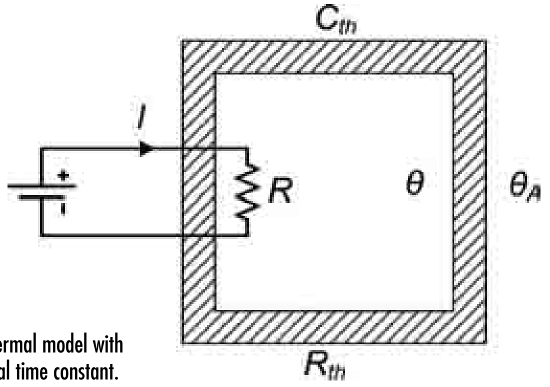


Figure 2.5: Thermal model with a single thermal time constant.

The difference between the input power and the output power is used to elevate the temperature of the uniform object,

$$P_{in} - P_{out} = C_{th}\frac{d(\theta-\theta_A)}{dt} \tag{2.1}$$

The input power is the heat, $I^2R$, generated by the current on the resistor. The output power is the heat transfer, $\frac{\theta-\theta_A}{R_{th}}$ across the boundary of the object to its ambient. Therefore, Equation (2.1) is rewritten as,

$$I^2R - \frac{\theta-\theta_A}{R_{th}} = C_{th}\frac{d(\theta-\theta_A)}{dt} \tag{2.2}$$

By solving Equation (2.2) as a first order differential equation, a closed form solution is obtained,

$$\theta(t) = I^2R\cdot R_{th}\left(1-e^{-\frac{t}{\tau_{th}}}\right)+\theta_A \tag{2.3}$$

where tth=$R_{th}C_{th}$ is the thermal time constant of the uniform object.

If the constant current, *I*, flows in this uniform object for a sufficiently long time, i.e. $t\rightarrow\infty$, the final temperature of this uniform object is $\theta(\infty)=I^2R\cdot R_{th}+\theta_A$.

For a specific motor, it is designed to work under some maximum permissible temperature, $\theta_{\max}$ , determined by its stator winding insulation material [5]. This maximum permissible temperature determines the maximum permissible current through the stator winding,

$$I_{\max} = \sqrt{\frac{\theta_{\max} - \theta_A}{R \cdot R_{th}}} \qquad (2.4)$$

For a motor, if its stator current exceeds a predetermined value for certain time, the stator winding temperature will rise above its maximum permissible value. The microprocessor-based overload relay monitors the stator current and calculates the time to trip the motor and ensures proper motor operation below its stator winding maximum permissible temperature. Figure 2.6 shows the one possible implementation of the temperature estimation scheme by an equivalent electrical circuit, which consists of an R-C circuit and an Op-Amp.

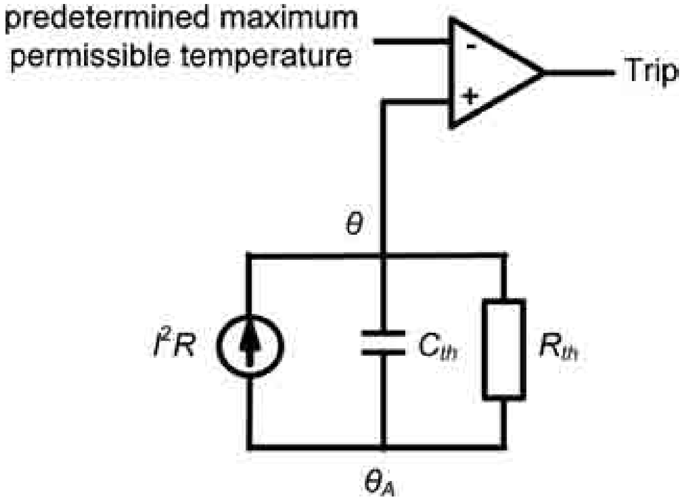


Figure 2.6: Equivalent electrical circuit of the temperature estimator with a single thermal time constant.

While Equations (2.3) and (2.4) are sufficient in predicting the stator winding temperature, it is usually difficult to obtain the thermal resistance and the thermal capacitance for a particular motor. Therefore, the full load current (FLC), service factor (SF) and trip class (TC) are used instead to calculate the time to trip.

From Equation (2.3), for a motor with its stator winding initially at the ambient temperature, under given constant current, *I*, and with a known stator winding maximum permissible temperature $\theta_{\max}$, the time needed to trip this motor is,

$$t = \tau_{th} \ln\left[\frac{I^2 R \cdot R_{th}}{I^2 R \cdot R_{th} - (\theta_{\max} - \theta_A)}\right] \qquad (2.5)$$

Substituting $(\theta_{\max} - \theta_A)$ in Equation (2.5) with $I^2_{max}$ $R\text{-}R_{th}$ According to Equation (2.4), gives,

$$t = \tau_{th} \ln\left(\frac{I^2 R \cdot R_{th}}{I^2 R \cdot R_{th} - I^2_{\max} R \cdot R_{th}}\right) = \tau_{th} \ln\left(\frac{I^2}{I^2 - I^2_{\max}}\right) \qquad (2.6)$$

By defining service factor to be,

$$SF = \frac{I_{\max}}{I_{\text{rated}}} \qquad (2.7)$$

Equation (2.6) is further simplified,

$$t = \tau_{th} \ln\left(\frac{I^2_{pu}}{I^2_{pu} - SF^2}\right) \qquad (2.8)$$

$$\text{where } I_{pu} = \frac{I}{I_{\text{rated}}}.$$

Trip class, often denoted as $t_{6X}$, is defined to be the maximum time [seconds] for an overload trip to occur when a cold motor's operating current is six times its rated current. From Equation (2.8),

$$t_{6X} = T_{th} \ln\left(\frac{6^2}{6^2 - SF^2}\right) \qquad (2.9)$$

Therefore, the relationship between $t_{6X}$ and $t_{th}$ can be established once the service factor of that specific motor is known. Table 2.1 shows the relationship between the thermal time constant and the trip class at different service factors according to Equation (2.9).

| Service Factor | Thermal Time Constant |
|---|---|
| 1.00 | 35.5 $t_{6X}$ |
| 1.05 | 32.0 $t_{6X}$ |
| 1.10 | 29.2 $t_{6X}$ |
| 1.15 | 26.7 $t_{6X}$ |

Table 2.1: Relationship between $t_{th}$ and $t_{6X}$ at different service factors

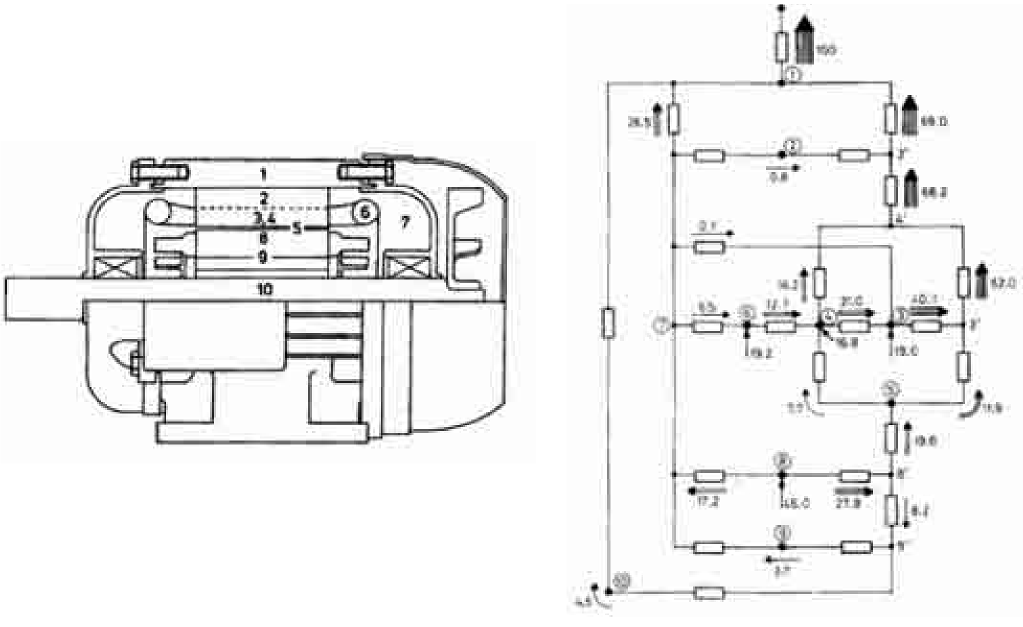
As a brief conclusion, given the full load current, the service factor and the trip class of a motor, the time to trip can be calculated from Table 2.1 and Equation (2.8). For example, for the test motor given in Table A.1, the service factor is 1.15, and its trip class is 20. Therefore, for an overload with $I = 1.5 I_{\text{rated}}$, the time to trip is,

$$t = 26.7 \cdot t_{6X} \ln\left(\frac{1.5^2}{1.5^2 - 1.15^2}\right) = 26.7 \times 20 \times 0.8862 = 473.23 \text{ (sec)} \qquad (2.10)$$

### 2.1.3 COMPLEX THERMAL NETWORKS

The thermal model of a single thermal time constant is derived from the thermal behavior of a uniform object. However, the motor is not thermally homogeneous, the temperature rise at various parts of the motor, such as the stator, the rotor, or the iron core, is different. Even areas in the same part, such as the stator slot winding and the end winding, have different thermal characteristics. Therefore, complex thermal networks have been proposed as one type of thermal model-based temperature estimation techniques [6], [23]-[26].

Figure 2.7 illustrates one type of the complex thermal networks proposed in reference [23]. Figure 2.7(a) shows the structure of the totally enclosed fan-cooled (TEFC) induction machine along with the specific locations where the temperature is estimated. Figure 2.7(b) shows how each of the ten components are linked to form a network of an induction machine thermal model and the actual heat flow between them. The temperature of the stator components, such as stator winding, stator end winding, stator core and stator teeth can be estimated using this model. However, the thermal resistors and capacitors need to be evaluated in advance from the physical dimensions and construction materials of the motor.



(a) Detailed construction of motor #1

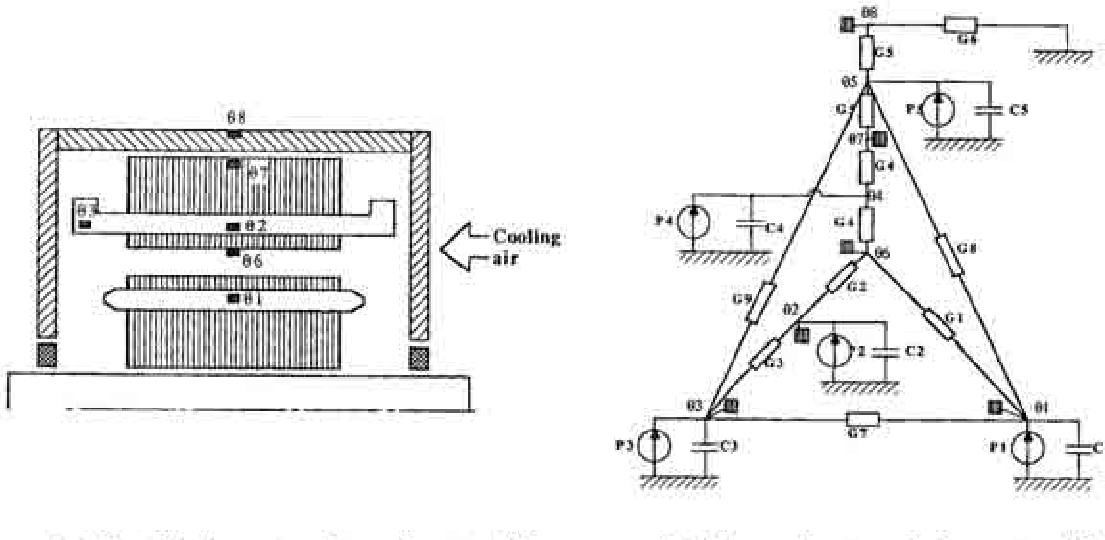
(b) Heat flow inside motor #1

1. Motor frame
2. Stator back iron
3. Stator teeth
4. Stator slot winding
5. Air gap
6. Stator end winding
7. End cap air
8. Rotor winding
9. Rotor back iron
10. Motor shaft

Figure 2.7: Thermal model by a complex thermal network for induction machine #1.

To avoid calculation of the thermal resistances and capacitances from the physical dimensions and construction materials of an induction machine, some researchers propose a complex thermal network based on parameter estimation, as shown in Figure 2.8 [26]. First, the embedded thermal sensors measure the temperatures at various locations inside the induction machine, as indicated in Figure 2.8(a). The thermal resistances and capacitances are then identified online by applying a recursive least square method on the thermal network illustrated in Figure 2.8(b). Once the thermal resistances and capacitances are identified, the thermal network is capable of predicting the temperatures at various locations inside the motor.

Although the parameter estimation technique used here eliminates the need to calculate the thermal resistances and capacitances from physical dimensions and construction materials of an induction machine, it requires high-precision temperature measurements from the embedded thermal sensors. This is often impractical for small-size mains-fed induction machines due to economic reasons.



(a) Detailed construction of motor #2

(b) Thermal network for motor #2

1. Rotor cage center
2. Stator embedded winding center
3. Stator end winding center
4,6,7. Stator core
5. Frame and end brackets

Figure 2.8: Thermal model by a complex thermal network for induction machine #2.

## 2.2 TEMPERATURE ESTIMATION BASED ON MOTOR PARAMETERS

The thermal model-based temperature estimation techniques give an estimate of the stator winding temperature based on the thermal model, and the knowledge of the thermal parameters in the model is very crucial in giving an accurate temperature estimate. In practice, the thermal capacitance and resistance are normally predetermined by a set of parameters for a class of motors of the same ratings, such as full load current, service factor and trip class. Consequently, the thermal model is incapable of giving an accurate stator winding temperature estimate tailored to a specific motor's thermal capacity. The parameter-based temperature estimation techniques, on the other hand, derive average stator and rotor temperatures from the stator and rotor resistances, respectively. Compared with the temperatures estimated from the thermal models, the temperatures estimated from the stator resistance, $R_s$, and the rotor resistance, $R_r$, are more direct measures of the stator temperature, $\theta_s$, and the rotor temperature, $\theta_r$, respectively.

According to reference [19], the temperature and the resistance have the following relationship,

$$R_2 = R_1 \cdot \frac{\theta_2 + k}{\theta_1 + k} \tag{2.11}$$

where $\theta_1$ represents the reference temperature [°C]; $R_1$ and $R_2$ are the resistances [$\Omega$] at temperature $\theta_1$ and $\theta_2$, respectively; $k$ is the inferred temperature coefficient for zero resistance and varies for different materials: for 100% International Annealed Copper Standard (IACS) conductivity copper[1], it is 234.5, for aluminum with a volume conductivity of 62%, it is 225.

In parameter-based temperature estimation techniques, once the resistance is estimated, the temperature is calculated from Equation (2.11), which is rewritten as,

$$\theta_2 = \frac{R_2}{R_1} \cdot (\theta_1 + k) - k \tag{2.12}$$

As indicated by Equation (2.12), the key issue in parameter-based temperature estimation is an accurate estimate of the resistance. Since the purpose of the temperature monitoring is to protect motors from overheating in its stator winding, direct estimation of the stator resistance now becomes the focus of this review of previous research.

There are two major approaches to estimating the stator resistance:

1) Resistance estimation based on the induction machine model

2) Resistance estimation using DC injection.

These two approaches are summarized in this section.

### 2.2.1 INDUCTION MACHINE MODEL-BASED RESISTANCE ESTIMATION

Estimation schemes for $R_s$ have been proposed mainly for improving the performance of field oriented drives at low speed [27]-[30], or for obtaining a better estimate of shaft speed for speed sensorless control at low speed [31]-[34]. This section reviews the basic principles used in $R_s$ estimation techniques.

Using a synchronously rotating reference frame $(\omega = \omega_e)$ and aligning the current vector with the d-axis $(i_{qs}^e = p i_{qs}^e = 0)$ in the *q-d* coordinates, the operation of a symmetrical induction machine under steady state $(p\lambda_{qds}^e = p\lambda_{qdr}^e = 0)$ is described by [35],

$$v_{qs}^e = \omega_e \lambda_{ds}^e, \quad v_{ds}^e = R_s i_{ds}^e - \omega_e \lambda_{qs}^e \tag{2.13}$$

$$0 = R_r i_{qr}^e + s\omega_e \lambda_{dr}^e, \quad 0 = R_r i_{dr}^e - s\omega_e \lambda_{qr}^e \tag{2.14}$$

$$\lambda_{qs}^e = L_m i_{qr}^e, \quad \lambda_{ds}^e = L_s i_{ds}^e + L_m i_{dr}^e \tag{2.15}$$

$$\lambda_{qr}^e = L_r i_{qr}^e, \quad \lambda_{dr}^e = L_r i_{dr}^e + L_m i_{ds}^e \tag{2.16}$$

where $R_s$, $R_r$ are the stator and rotor resistance respectively; $L_s$, $L_r$, $L_m$ are the stator, rotor and mutual inductance respectively; $\omega_e$ is the angular speed [rad/s] of the synchronous reference frame; $s$ is the slip; and $p$ is the differential operator, $\frac{d}{dt}$; [illegible] is the slip frequency defined as the difference between the synchronous speed, $\omega_e$, and the rotor speed, $\omega_r$; $\lambda_{qds}$ and $\lambda_{qdr}$ are the stator and rotor flux linkage, respectively.

By eliminating $i_{qdr}^e$ and $\lambda_{qds}^e$, Equations (2.13)-(2.16) are further reduced to,

$$v_{qs}^{es} = \omega_e \left( \sigma L_s i_{ds}^{es} + \frac{L_m}{L_r} \lambda_{dr}^{es} \right) \tag{2.17}$$

$$v_{ds}^{es} = R_s i_{ds}^{es} - \omega_e \frac{L_m}{L_r} \lambda_{qr}^{es} \tag{2.18}$$

$$0 = \frac{R_r}{L_r} \lambda_{qr}^{es} + s\omega_e \lambda_{dr}^{es} \tag{2.19}$$

$$0 = \frac{R_r}{L_r} \left( \lambda_{dr}^{es} - L_m i_{ds}^{es} \right) - s\omega_e \lambda_{qr}^{es} \tag{2.20}$$

Equations (2.17), (2.19) and (2.20) can be used to calculate $R_r$. By eliminating $\lambda_{qr}^e$, expressions for estimates of ledr and $R_r$, which are independent of $R_s$, are,

$$\hat{\lambda}_{dr}^e = \frac{L_r}{\omega_e L_m} v_{qs}^e + \frac{\sigma L_s L_r}{L_m} i_{ds}^e \tag{2.21}$$

$$\hat{R}_r = \frac{s\omega_e \cdot L_r}{\sqrt{\dfrac{L_m i_{ds}^e}{\hat{\lambda}_{dr}^e} - 1}} \tag{2.22}$$

Similarly, $R_s$ is calculated from (2.18), (2.20)-(2.22) as,

$$\hat{R}_s = \frac{v_{ds}^e}{i_{ds}^e} - \frac{s\omega_e^2 L_m \hat{\lambda}_{dr}^e}{\hat{R}_r i_{ds}^e} \tag{2.23}$$

The overall structure of the $R_r$ and $R_s$ estimator is shown in Figure 2.9.

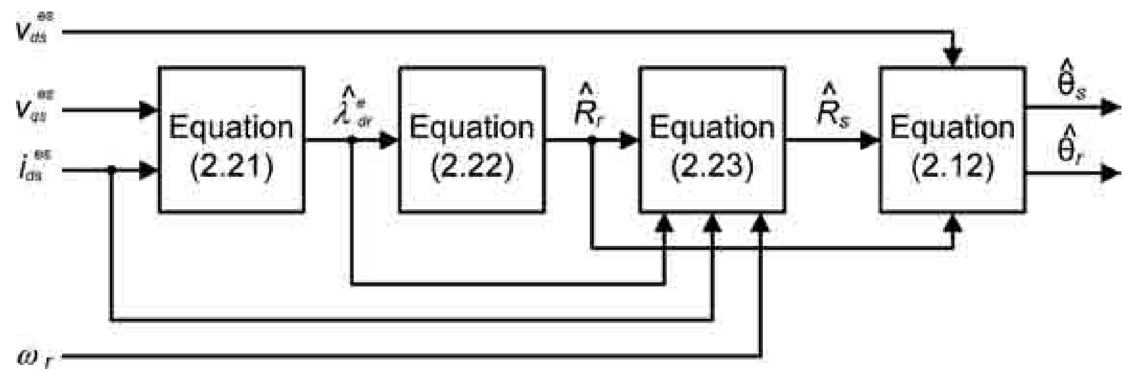


Figure 2.9: Overall structure of the induction machine model-based $R_r$ and $R_s$ estimator.

### 2.2.2 RESISTANCE ESTIMATION USING DC INJECTION

The DC injection circuit proposed in references [15]-[16] and [36]-[37] consists of a power MOSFET and an external resistor connected in parallel. Figure 2.10 shows the DC equivalent circuit of the motor, source, and DC injection circuit from the source to the motor terminals in one phase. The DC injection circuit operates in two modes: DC injection mode (DIM) and normal mode (NM: no injection of DC), for intermittent injection of a DC bias into the motor.

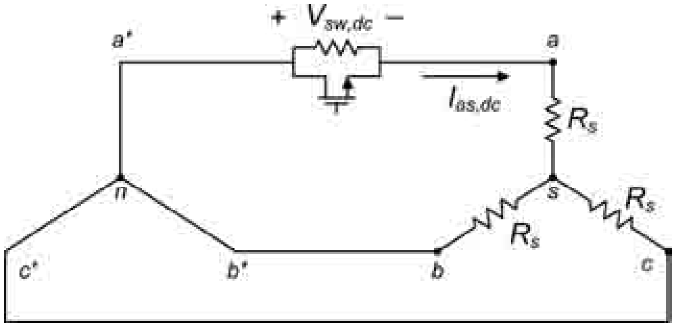
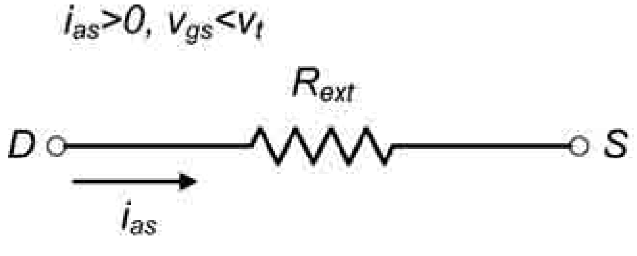


Figure 2.10: DC equivalent circuit of DC injection circuit and the motor.

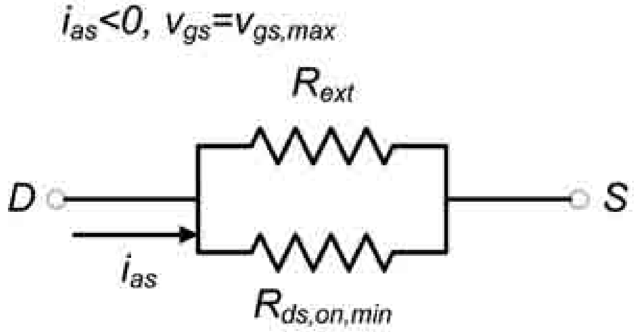
During the DC injection mode, the FET is turned off when $i_{as} > 0$, and turned on when $i_{as} < 0$; the equivalent circuits for each case is shown in Figure 2.11(a) and (b), respectively, and the *v-i* characteristics under DIM is shown in Figure 2.11(c). The asymmetrical resistance causes the voltage drop across the circuit to be asymmetrical (DC component in $v_{sw}$), resulting in the injection of a DC current component into the motor. Under DIM, $R_s$ is updated using,

$$\hat{R}_s = \frac{v_{as,dc}}{i_{as,dc}} = \frac{2\cdot v_{ab,dc}}{3\cdot i_{as,dc}} = -\frac{2\cdot v_{sw,dc}}{3\cdot i_{as,dc}} \qquad (2.24)$$

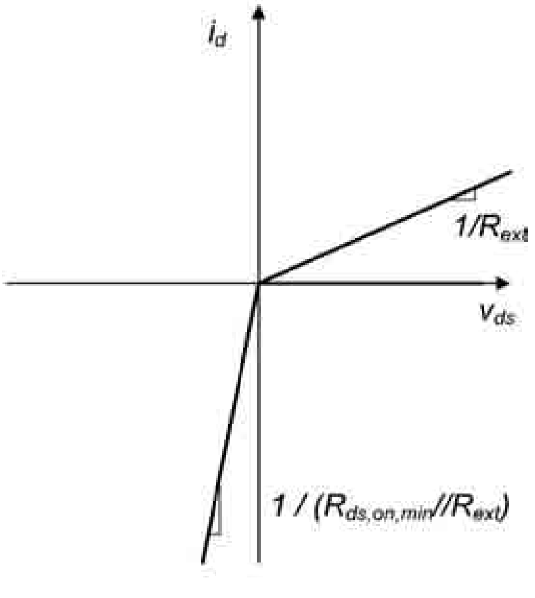
The DC injection scheme causes torque pulsation inside the motor and power dissipation in both the stator winding and $R_{ext}$. To adjust the torque distortion and power dissipation to be within an acceptable level, the value of $R_{ext}$ is adjusted depending on the nominal $R_s$ and the rated $i_{as}$. In addition, the variation of the stator winding temperature is slow, therefore it is not necessary to inject a constant DC bias into the motor and estimate $R_s$ continuously. As a result, the DC injection circuit can be operated under NM in between DIMs, by setting $v_{gs}$ to $V_{gs}$,*on* (FET on). The equivalent circuit and *v-i* characteristics of the DC injection circuit under NM are shown in Figure 2.12(a) and (b), respectively.



(a) operation at positive haversine in DIM



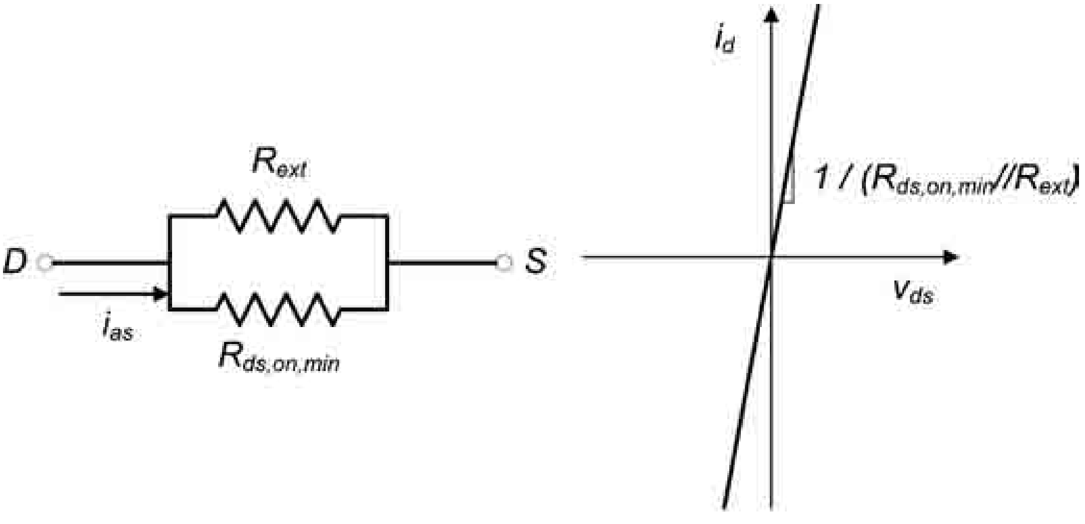
(b) operation at negative haversine in DIM



(c) *v-i* characteristics

Figure 2.11: Equivalent circuit during DC injection mode.

The circuit needs to be operated in DIM for a minimum time interval ($t_{DIM}$) that is sufficient for obtaining an accurate estimate of $R_s$. Between two subsequent DIMs, the DC injection circuit works in normal model. The length of the interval ($t_{NM}$) is determined based on how frequently an $R_s$ estimate is required. When operating in NM between the DIMs, there is no torque distortion in the motor and the power dissipation is significantly lower than that under DIM. The suggested $t_{DIM}$ and $t_{NM}$ are 0.25s and 29.75s respectively [37]. The overall circuit operates with very low power dissipation and short torque pulsation intervals.



(a) operation in NM

(b) $v$-$i$ characteristics

Figure 2.12: Equivalent circuit during normal mode.

### 2.3 COMPARISON OF DIFFERENT TEMPERATURE ESTIMATION SCHEMES

Rules 430-32 (a) and 430-125 (b) of reference [38] stipulate that each motor shall be protected against overload by either an integral protector or an external overload device. Two major techniques in estimating the stator winding temperature, the thermal model-based temperature estimation (TMTE) techniques and the parameter-based temperature estimation (PTE) techniques, are presented here. Each of them has their own advantages and disadvantages.

For the thermal model-based temperature estimation techniques, the stator winding temperature is calculated from measurements of stator currents only. Therefore they are non-intrusive and provide an estimated stator winding temperature within a certain confidence level. In addition, they are robust and efficient. However, both the dual-element time-delay fuses and the thermal models with a single time constant cannot provide an accurate temperature estimation at all times, while the complex thermal networks need either full knowledge of the machine's physical dimensions and construction materials or high-precision temperature measurements from embedded thermal sensors to perform the parameter estimation.

Parameter-based temperature estimation techniques, on the other hand, provide a far more accurate estimate of the temperature than the thermal model-based temperature estimation techniques, since the stator resistance is a direct indicator of its temperature. This type of method is capable of responding to all of the situations where the thermal model parameters change due to the change in the machine operating condition or its ambient temperature. Since the stator temperature estimate is accurate, excessive temperature rise due to abnormal cooling situations can be detected, which is normally not possible using conventional TMTE method. However, as discussed in Section 2.2, the induction machine model-based resistance estimation is highly susceptible to the parametric errors from other measurements and parameters, while the resistance estimation using dc injection may cause torque pulsations inside the motor and additional power dissipation in the stator winding.

The detailed advantages and the disadvantages of the TMTE and PTE methods are summarized below in Table 2.2.

### 2.4 SUMMARY

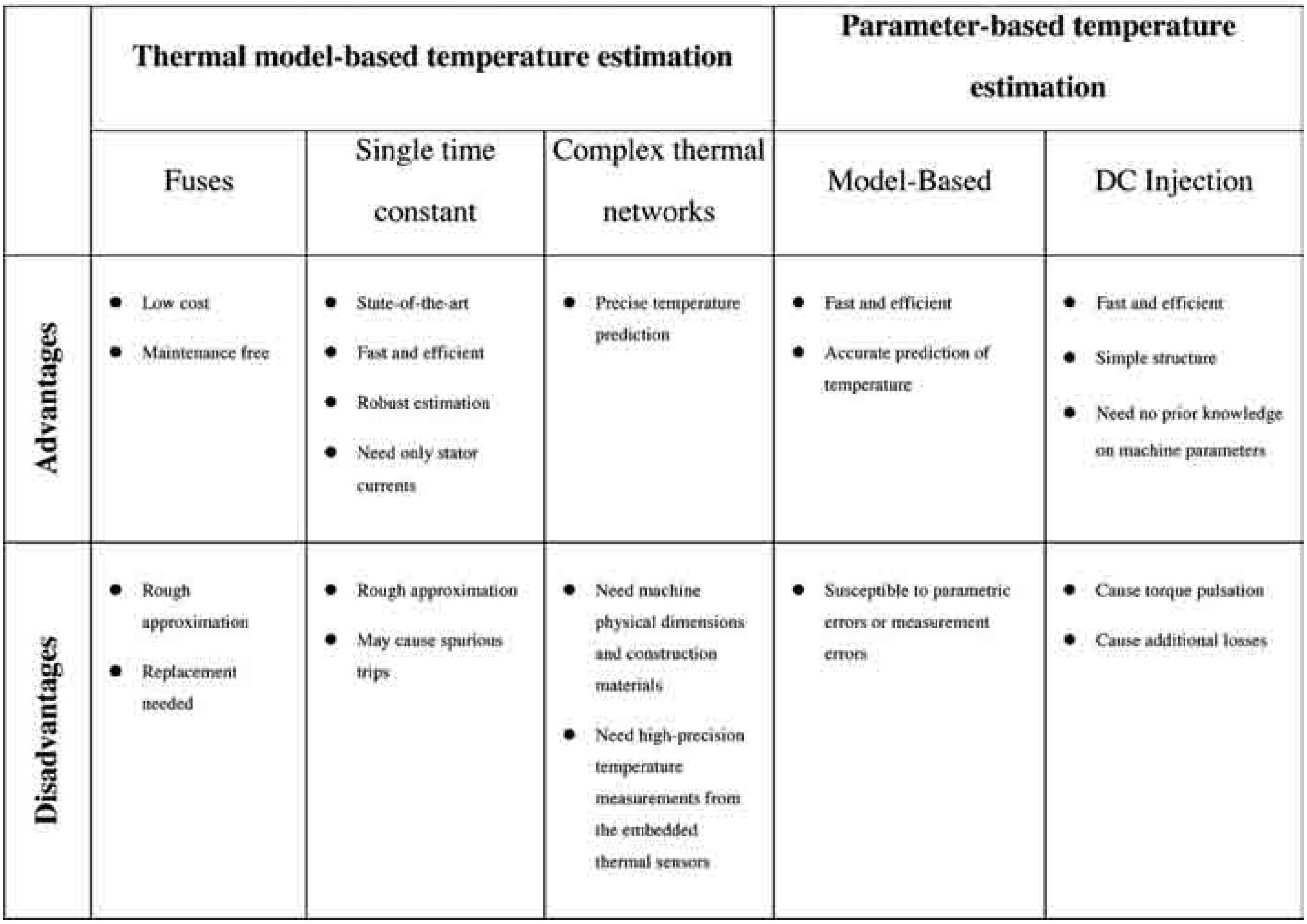
Based on the discussion of the causes and consequences of the overload, three methods to obtain stator winding temperature are discussed. Due to the scope of this research, two types of temperature estimation techniques developed so far, the thermal model-based temperature estimation techniques and the parameter-based temperature estimation techniques, remain the focus.

As presented in Section 2.1, the thermal model-based temperature estimation technique uses a thermal model to approximate the internal heating effects of the motor, while the parameter-based temperature estimation technique derives the stator winding temperature from the estimated stator resistance, discussed in Section 2.2. The underlying mechanisms of these two types of temperature estimation techniques are briefly outlined. Their advantages and disadvantages are given in Section 2.3.

## INDUCTION MACHINE THERMAL ANALYSIS

Microprocessor-based motor overload protection relays, which represent the state-of-the-art in motor protection, rely on the motor heat transfer models to predict the stator winding temperature. Thermal models with a single thermal capacitor and a single thermal resistor are widely used in the industry. The thermal capacitance and resistance are normally pre-determined by a set of parameters for a given class of motors, such as full load current, service factor and trip class [22].

Once these parameters are set by plant operators or field engineers, the relay is supposed to protect the motor utilizing the measured phase current magnitudes. However, since these parameters are specified to protect the motor against the so-called "transient overloads", where inrush current ranges from 250% up to 1,000% of the motor's rated current, the relay may not provide adequate overload protection during "running overloads", where the stator current is between 100% and 200% of the motor's rated current [6]. This inadequacy is the result of changes in the motor's cooling capacity. During a transient overload, such as a mechanical jam, an adiabatic internal heating is assumed due to its large inrush current and short duration,



| | Thermal model-based temperature estimation | | | Parameter-based temperature estimation | |
|---|---|---|---|---|---|
| | Fuses | Single time constant | Complex thermal networks | Model-Based | DC Injection |
| Advantages | • Low cost<br>• Maintenance free | • State-of-the-art<br>• Fast and efficient<br>• Robust estimation<br>• Need only stator currents | • Precise temperature prediction | • Fast and efficient<br>• Accurate prediction of temperature | • Fast and efficient<br>• Simple structure<br>• Need no prior knowledge on machine parameters |
| Disadvantages | • Rough approximation<br>• Replacement needed | • Rough approximation<br>• May cause spurious trips | • Need machine physical dimensions and construction materials<br>• Need high-precision temperature measurements from the embedded thermal sensors | • Susceptible to parametric errors or measurement errors | • Cause torque pulsation<br>• Cause additional losses |

Table 2.2: Comparison of different temperature estimation techniques

and the temperature inside the induction machine increases rapidly. During a running overload, the continuous rotation of the rotor provides a certain degree of cooling, which leads to a gradual increase in the motor's internal temperature. In addition, the cooling capability can also change in service due to, for example, a broken cooling fan or a clogged motor casing [15]. The conventional relay cannot adjust itself to yield an accurate estimate of the stator winding temperature tailored to the specific motor's cooling capability. The inability of the conventional thermal model to respond to the changes in motor's cooling capability with updated thermal resistance may lead to an accelerated and often irreversible deterioration of the stator winding insulation, and ultimately a reduced motor life or even total motor failure [4].

In this section, the thermal behavior of small to medium size induction machines is analyzed. Based on the analysis of the machine's thermal behavior via the thermal network with thermal resistors and thermal capacitors, a hybrid thermal model is proposed and analyzed.

### 3.1 ANALYSIS OF INDUCTION MACHINE THERMAL BEHAVIORS

It is assumed that the thermal behavior of the stator end winding or the rotor inside an induction machine during running overloads can be modeled by a thermal network with thermal resistors and thermal capacitors. The thermal resistances and thermal capacitances do not change over the time. The state-space representation of induction machine thermal models is derived from the thermal network and the thermal behaviors of the induction machine during various duty types are discussed.

### 3.1.1 STATE-SPACE REPRESENTATION OF INDUCTION MACHINE THERMAL MODELS

For a typical induction machine, its thermal dynamics can be characterized by a lumped-parameter thermal model with thermal conductors and thermal capacitors. The state-space representation of this model is,

$$\dot{\boldsymbol{\theta}}(t) = \mathbf{A}\boldsymbol{\theta}(t) + \mathbf{B}\mathbf{P}_{loss}(t) \tag{3.1}$$

$$y(t) = \mathbf{C}\boldsymbol{\theta}(t) \tag{3.2}$$

where $\boldsymbol{\theta}$ [ºC] is a vector containing nodal temperature rises above the ambient at different locations inside a motor, including the stator winding, the rotor cage and the iron core; $\mathbf{P}_{\text{loss}}$ [*W*] is a vector containing power losses, such as the stator $I^2R$ loss, the rotor $I^2R$ loss and the core loss.

The system matrix $\mathbf{A}=-\mathbf{C}_t^{-1}\boldsymbol{\Lambda}_t$, where $\mathbf{C}_t$ [*J*/ºC] is a diagonal matrix containing the thermal capacitances of various components, and $\boldsymbol{\Lambda}_t$ [W/ºC] is a symmetrical matrix of thermal conductances between various parts of the motor. Since $\boldsymbol{C}_t$ is a diagonal matrix and $\boldsymbol{\Lambda}_t$ is symmetrical, the eigenvalues of the system matrix **A**, denoted as $\lambda_1, \lambda_2, \ldots, \lambda_n$, are all real and negative [39]. The input matrix **B** is related to the thermal capacitance matrix by $\mathbf{B}=\mathbf{C}_t^{-1}$. The output matrix, **C**, represents the relationship between the nodal temperature rises, q, and the measured quantity, y.

An example of a full order thermal network is shown in Figure 3.1 [25]. Node 1, 2, 3, 4 and 5 represent stator core, stator slot winding, stator end winding, rotor cage and rotor core, respectively. $C_i$ [*J*/°C] is associated with the thermal capacitance at node *i*. $\Lambda_{ij}$ [°C/W] is the thermal conductance between nodes *i* and *j*. $P_i$ [W] represents the power loss at node *i*, and $\theta_i$ [°C] is the temperature rise with respect to the motor ambient at node *i*. The values of $C_i$ and $\Lambda_{ij}$ are marked in Figure 3.1.

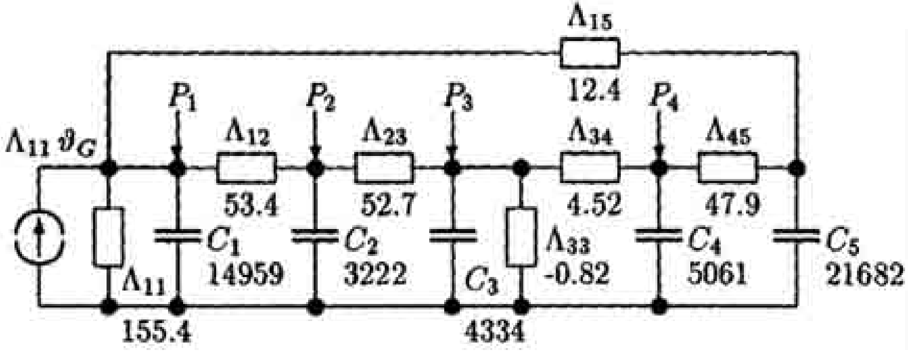


Figure 3.1: Thermal Network and Parameters [25].

The thermal network shown in Figure 3.1 is described by,

$$\mathbf{C}_t\dot{\boldsymbol{\theta}}+\boldsymbol{\Lambda}_t\boldsymbol{\theta}=\mathbf{P}_{loss} \tag{3.3}$$

where $\boldsymbol{\theta}=[\theta_1\ \theta_2\ \theta_3\ \theta_4\ \theta_5]^T$, $\mathbf{P}_{loss}=[P_1\ P_2\ P_3\ P_4\ P_5]^T$ with $P_5=0$. The parameter matrices $\mathbf{C}_t$ and $\boldsymbol{\Lambda}_t$ are,

$$\mathbf{C}_t=\mathrm{diag}\begin{bmatrix}C_1 & C_2 & C_3 & C_4 & C_5\end{bmatrix} \tag{3.4}$$

$$\boldsymbol{\Lambda}_t=\begin{bmatrix}\Lambda_{11}+\Lambda_{12}+\Lambda_{15} & -\Lambda_{12} & 0 & 0 & -\Lambda_{15}\\ -\Lambda_{12} & \Lambda_{12}+\Lambda_{23} & -\Lambda_{23} & 0 & 0\\ 0 & -\Lambda_{23} & \Lambda_{23}+\Lambda_{33}+\Lambda_{34} & -\Lambda_{34} & 0\\ 0 & 0 & -\Lambda_{34} & \Lambda_{34}+\Lambda_{45} & -\Lambda_{45}\\ -\Lambda_{15} & 0 & 0 & -\Lambda_{45} & \Lambda_{15}+\Lambda_{45}\end{bmatrix} \tag{3.5}$$

According to Equations (3.1)-(3.2), the state-space representation of the thermal network is,

$$\mathbf{A}=-\mathbf{C}_t^{-1}\boldsymbol{\Lambda}_t=\begin{bmatrix}-\frac{\Lambda_{11}+\Lambda_{12}+\Lambda_{15}}{C_1} & \frac{\Lambda_{12}}{C_1} & 0 & 0 & \frac{\Lambda_{15}}{C_1}\\ \frac{\Lambda_{12}}{C_2} & -\frac{\Lambda_{12}+\Lambda_{23}}{C_2} & \frac{\Lambda_{23}}{C_2} & 0 & 0\\ 0 & \frac{\Lambda_{23}}{C_3} & -\frac{\Lambda_{23}+\Lambda_{33}+\Lambda_{34}}{C_3} & \frac{\Lambda_{34}}{C_3} & 0\\ 0 & 0 & \frac{\Lambda_{34}}{C_4} & -\frac{\Lambda_{34}+\Lambda_{45}}{C_4} & \frac{\Lambda_{45}}{C_4}\\ \frac{\Lambda_{15}}{C_5} & 0 & 0 & \frac{\Lambda_{45}}{C_5} & -\frac{\Lambda_{15}+\Lambda_{45}}{C_5}\end{bmatrix} \tag{3.6}$$

$$\mathbf{B}=\mathbf{C}_t^{-1}=\mathrm{diag}\begin{bmatrix}\frac{1}{C_1} & \frac{1}{C_2} & \frac{1}{C_3} & \frac{1}{C_4} & \frac{1}{C_5}\end{bmatrix} \tag{3.7}$$

To select temperature rise at the stator end winding (node 3) as the output, set $\mathbf{C}=[0\ 0\ 1\ 0\ 0]^T$.

### 3.1.2 INDUCTION MACHINE THERMAL BEHAVIORS UNDER DIFFERENT DUTY TYPES

Many motor manufacturers supply motors with continuous running duty ratings, designated as duty type S1 according to [40], as default options to their clients. These motors are supposed to be operated at constant loads for sufficient time until they reach their thermal equilibriums. According to Equations (3.1)-(3.7), the temperature rise in a particular spot inside the motor with such duty type is described by,

$$\theta(t)=\sum_{i=1}^{N}\theta_{ss,i}\left(1-e^{-t/\tau_i}\right)+\theta_{\mathrm{ambient}} \tag{3.8}$$

where $\tau_i=-1/\lambda_i$ is a time constant associated with the thermal characteristics of various parts of the motor; $\theta_{ss,i}$ is the steady-state temperature rise corresponding to $\tau_i$ if the thermal equilibrium can be established inside the motor.

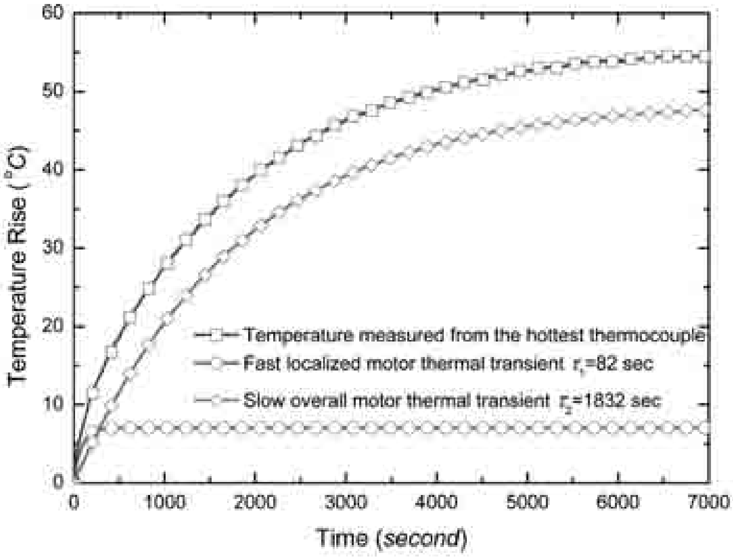
As indicted by Equation (3.8), all the eigenvalues of the system matrix manifest themselves in terms of time constants in q (t). For example, there are altogether 5 time constants for the induction motor described by the sample thermal network of Figure 3.1: $\tau_1$=23.91 sec, $\tau_2$=69.84 sec, $\tau_3$=85.06 sec, $\tau_4$=263.11 sec and $\tau_5$=2361.13 sec. The small time constants correspond to fast thermal transients. They are usually associated with localized heating inside the motor, such as a rapid temperature rise in the stator end winding upon an increase in the motor's load. The large time constants, on the other hand, characterize the motor's thermal behavior in the long run. They are generally related to the overall heat dissipation capability of the motor.

When a motor is operated with duty type S1, both the fast and the slow thermal transients can be observed. For a 7.5 hp TEFC test motor with parameters shown in Table A.3, the temperature measurements captured at its stator end winding indicate that there are two major thermal transients: a fast one with $\tau_1$=82 sec and a slow one with $\tau_2$=1832 sec. As indicated in Figure 3.2(a), the fast thermal transient has a steady-state temperature rise of $\theta_{ss,1}$=7.04 °C, while the slow thermal transient has a steady-state temperature rise of $\theta_{ss,2}$=47.79 °C. Figure 3.2(a) also shows that the fast thermal transient reached its steady-state value after approximately 500 sec from the instant when the motor started. From then on, the slow thermal transient becomes more and more apparent as time increases.

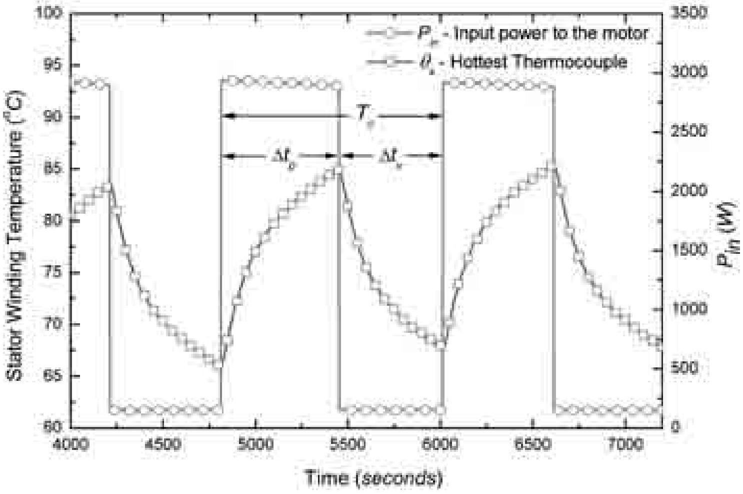
In practice, however, motors are often subjected to continuous-operation periodic duties, denoted as duty type S6 [40]. Each cycle of this duty type consists of a time of operation at constant load, $\Delta t_P$, and a time of operation at no-load, $\Delta t_V$. Thermal equilibrium is usually not reached during the time with load.

In the case that the motor is operated with duty type S6, and the operation time at constant load, $\Delta t_P$ is much shorter than the large time constants, the fast thermal transients dominate the motor's temperature response. As $\Delta t_P$ increases, the fast thermal transients reach their steady-state values, and the slow thermal transients begin to dominate the motor's temperature response. This trend continues until $\Delta t_P$ is sufficiently large that an overall thermal equilibrium is established inside the motor.

To illustrate the above discussion, the 7.5 hp test motor was subjected to periodic duty cycles with a cyclic duration factor $(\Delta t_p/T_c)$ of 50%. Figure 3.2(b) shows the stator end winding temperature, along with the input power, from one set of experiments with $\Delta t_p$ =10 min. The result obtained by fitting the single thermal time constant to the measured temperature is $\tau$=239 sec. For different values of $\Delta t_p$, the corresponding ther- $\Delta t_p$ time constants are: $\tau$=180 sec when Dtp =5 min; $\tau$=408 sec when $\Delta t_p$ =20 min; and $\tau$=481 sec when $\Delta t_p$ =30 min.



(a) Motor operation with duty type S1



(b) Motor operation with duty type S6

Figure 3.2: Stator winding temperature rise for the 7.5 hp TEFC motor.

## 3.2 HYBRID THERMAL MODELS OF INDUCTION MACHINES

As discussed in detail the previous section as well as Section 2.1.3, thermal networks, derived either from theoretical calculations based on a comprehensive knowledge of the motor's physical dimensions and construction materials [23]-[24], or system identification schemes based on extensive temperature measurements at different locations inside a motor [25]-[26], can be used to model induction machine temperature rise from internal losses. However, for low-cost industrial applications with induction machines up to 100 hp, the motor's physical dimensions and construction materials are often not readily available, and extensive temperature measurements at different locations inside a motor require expensive installation of high-precision thermal sensors. Therefore, a simplified thermal model, which depends only on information from voltage and current sensors, is preferred.

Hybrid thermal models are proposed in this section to correlate the voltage and current measurements to the stator winding temperatures. The model parameters are loosely associated with aspects of machine design and provide reasonable accuracy to the estimation of the stator winding temperature during induction machine operation with running overload.

### 3.2.1 FULL ORDER HYBRID THERMAL MODEL

The full order hybrid thermal model is first introduced in this section along with the explanations of its parameters. Then the heat flow in this full order hybrid thermal model is analyzed by correlating the machine thermal parameters with the machine design, and conclusions are made with respect to the full order hybrid thermal model.

#### 3.2.1.1 DEFINITION OF THE FULL ORDER HYBRID THERMAL MODEL

A hybrid thermal model with lumped thermal capacitors and resistors is presented in Figure 3.3 to safeguard the stator winding hot spot against excessive heating during running overload conditions. It approximates the stator and rotor thermal characteristics. The model parameters are loosely associated with aspects of the machine design.

The quantities, qs and qr, are temperature rises [ºC] above ambient on the $\theta_s$tor an$\theta_r$otor side, respectively. The power input, $P_s$ [W] is associated directly with the $I^2R$ loss generated in the stator winding. In addition, under constant supply voltage, the core loss generated in the stator teeth and the back iron contributes a fixed portion to the rise of qs. The power input, $P_r$, is associated mainly with the $I^2R$ loss in $\theta_s$ rotor bars and end rings. These losses are calculated from the induction machine equivalent circuit.

The thermal resistance, $R_1$ [ºC/W], represents the heat dissipation capability of the stator to the ambient through the combined effects of heat conduction and convection; the thermal resistance, $R_2$ [ºC/W], is associated with the heat dissipation capability of the rotor to its surroundings; the thermal resistance, $R_3$ [ºC/W], is associated with the heat transfer from the rotor to the stator across the air gap. Since the radiation only accounts for a small amount of energy dissipated for most induction machines, its effect can be safely ignored without introducing significant errors in the stator winding temperature estimation [8].

The thermal capacitances, $C_1$ and $C_2$ [J/ ºC], are defined to be the energy needed to elevate the temperature by one degree Celsius for the stator and rotor, respectively. The capacitance, $C_1$, represents the total thermal capacity of the stator windings, iron core and frame, while $C_2$ represents the combined thermal capacity of the rotor conductors, rotor core and shaft.

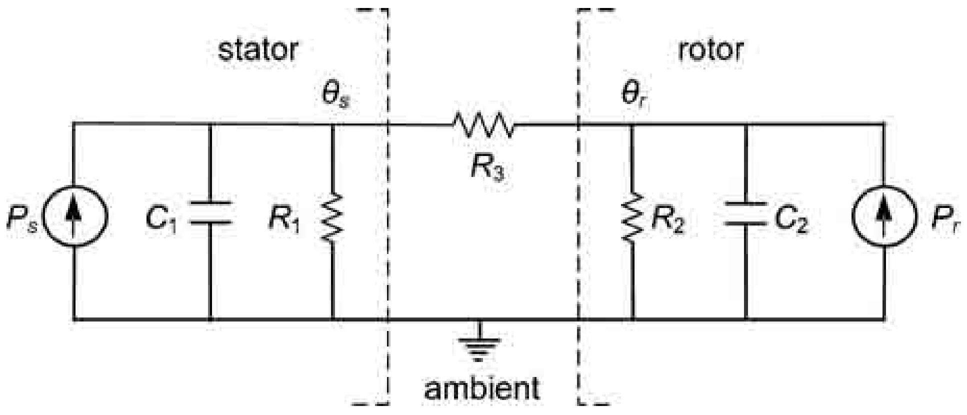


Figure 3.3: Full order hybrid thermal model for an induction motor.

The thermal characteristics of a motor manifest themselves in the rotor temperature, which can be observed from the rotor resistance via a parameter-based temperature estimator [13],[55]. Based on the estimated rotor temperature, the parameters of the proposed hybrid thermal model can therefore be adapted to reflect the motor's true cooling capability.

Compared with the conventional thermal model using a single thermal capacitor and a single thermal resistor, the hybrid thermal model incorporates the rotor losses and the heat transfer between the rotor and the stator. When properly tuned to a specific motor's cooling capacity, it is capable of tracking the stator winding temperature during running overloads, and therefore provides adequate protection against overheating. Furthermore, the hybrid thermal model is of adequate complexity compared to the complex thermal networks [23]-[26]. This makes it suitable for online parameter tuning.

### 3.2.1.2 ANALYSIS OF THE FULL ORDER HYBRID THERMAL MODEL

According to the definition of $C_1$ and $C_2$, a motor's stator and rotor thermal capacitances are fixed once the motor is manufactured. The motor's thermal resistances, however, are largely determined by its working environment. When a motor experiences an impaired cooling condition, $R_1$, $R_2$ and $R_3$ vary accordingly to reflect the changes in the stator and rotor thermal characteristics.

The knowledge of machine design can aid the parameter estimation and adaptation of $R_1$, $R_2$, $R_3$, $C_1$ and $C_2$ in the hybrid thermal model. NEMA standard MG-1 [5] specifies the major physical dimensions of induction machines up to 100 hp, with squirrel-cage rotors. Analysis of these design specifications gives a typical range for the thermal parameters. Based on this range, the online parameter tuning algorithm is then optimized to yield superior performance.

#### 3.2.1.2.1 ANALYSIS OF THE FULL ORDER HTM THERMAL PARAMETERS

For most induction machines up to 100 hp, $C_1$ is usually larger than $C_2$ due to the design of the motor. $R_1$ is typically smaller than $R_2$ because of the superior heat dissipation capability of the stator. $R_3$ is usually of the same order of magnitude as R1, and it correlates the rotor temperature to the stator temperature. These relationships are justified by a more detailed look at the machine design.

1) Relationship between $C_1$ and $C_2$: For most small-size induction machines with enclosures, the frame is an integral part of the machine. The frame acts as a heat sink with a large thermal capacitance. Therefore, even though the bulk parts of both the stator and rotor are laminated silicon steel of the same axial length, the thermal capacitance, $C_1$ is often larger than $C_2$ due to the inclusion of the frame. In addition, the stator winding overhang provides some extra thermal capacity to $C_1$. Normally, $C_1$ is 2 to 3 times larger than $C_2$ [41].

2) Relationship between $R_1$ and $R_2$: The frame of a small to medium size TEFC machine prevents the free exchange of air between the inside and outside of the case. Consequently, the heat transfer by means of convection from the rotor to the external ambient is restricted at running overload conditions. Only a limited amount of heat created by the rotor is transferred by means of conduction from the rotor bars and the end rings centripetally through the rotor iron to the shaft, and then flows axially along the shaft, through the bearings and finally reaches the ambient [23], [42]. In contrast, the stator dissipates heat effectively through the combined effects of conduction and convection. The axial ventilation through the air gap carries part of the heat away from the stator slot winding and the stator teeth, with the balance of the heat transferred radially through the stator iron and frame to the external ambient.

As an evidence of the good thermal conductivities of the stator iron and frame, the temperature of the stator slot winding is usually 5-10ºC lower than that of the stator end winding [23]-[24]. Some TEFC motors are even equipped with pin-type cooling fins on the surface of the frame, which makes it easier for the heat to be evacuated to the ambient [8]. In conclusion, $R_2$ is usually 4-30 times larger than $R_1$ at rated condition [41],[43].

3) Relationship between $R_1$ and $R_3$: Most TEFC induction machines in the low power range are characterized by a small air gap (typically around 0.25-0.75 mm) to increase efficiency. Furthermore, only a limited amount of air is exchanged between the inside and outside of the motor due to the enclosure. Therefore, among the rotor cage losses that are dissipated through the air gap, a significant portion is transferred to the stator by means of laminar heat flow, while the rest is passed to the endcap air inside the motor. These rotor cage losses, combined with the stator losses, travel through the stator frame and end shield and finally reach the ambient [8], [23]. Hence, the rotor and stator temperatures are highly correlated due to this heat flow pattern.

Reference [26] estimates that 65% of the overall rotor losses are dissipated through the air gap at rated condition. This indicates that $R_3$ is much smaller than $R_2$, and is usually of the same order of magnitude as $R_1$. Otherwise, the rotor losses would be dissipated mainly along the shaft instead of through the air gap.

#### 3.2.1.2.2 ANALYSIS OF THE FULL ORDER HTM TRANSFER FUNCTION

Assuming $P_s$ and $P_r$ are the inputs and $\theta_r$ is the output, the state space equations that describe the hybrid thermal model in Figure 3.3 are,

$$\begin{bmatrix}\dot{\theta}_s\\ \dot{\theta}_r\end{bmatrix}=\begin{bmatrix}-\frac{1}{C_1}\left(\frac{1}{R_1}+\frac{1}{R_3}\right) & \frac{1}{R_3C_1}\\ \frac{1}{R_3C_2} & -\frac{1}{C_2}\left(\frac{1}{R_2}+\frac{1}{R_3}\right)\end{bmatrix}\begin{bmatrix}\theta_s\\ \theta_r\end{bmatrix}+\begin{bmatrix}\frac{1}{C_1} & 0\\ 0 & \frac{1}{C_2}\end{bmatrix}\begin{bmatrix}P_s\\ P_r\end{bmatrix} \qquad (3.9)$$

$$y=\begin{bmatrix}0 & 1\end{bmatrix}\begin{bmatrix}\theta_s\\ \theta_r\end{bmatrix} \qquad (3.10)$$

Since the magnitude of the core loss is independent of the motor load level under constant supply voltage, and the core loss is far less than the stator $I^2R$ loss for most modern induction machines, it is therefore neglected in $P_s$ for the sake of convenience in the analysis. By taking into account only the $I^2R$ losses in the stator and rotor, $P_s$ and $P_r$ are,

$$P_s=3I_s^2R_s \qquad (3.11)$$

$$P_r=3I_s^2\frac{s^2\omega_e^2L_m^2}{R_r^2+s^2\omega_e^2L_r^2}R_r \qquad (3.12)$$

Assuming $K$ is the ratio of $P_r$ to $P_s$,

$$K=\frac{P_r}{P_s}=\frac{s^2\omega_e^2L_m^2}{R_r^2+s^2\omega_e^2L_r^2}\cdot\frac{R_r}{R_s} \qquad (3.13)$$

Since the temperature increases gradually inside the motor at running overload conditions, $K$ remains constant if the rotor speed does not change.

By substituting $P_r$ with $KP_s$ in Equation (3.9) and taking the Laplace transform, the transfer function between the input, $P_s$, and the output, $\theta_r$, in the s-domain, is,

$$Y(s)=\frac{b_1s+b_0}{a_2s^2+a_1s+a_0}P_s(s) \qquad (3.14)$$

where $a_0=R_1+R_2+R_3$; $a_1=C_1R_1R_3+C_1R_1R_2+C_2R_2R_3+C_2R_1R_2$; $a_2=C_1C_2R_1R_2R_3$; $b_0=R_1R_2+R_1R_2K+R_2R_3K$; $b_1=C_1R_1R_2R_3K$.

When the input to the hybrid thermal model is a step signal with a magnitude $c$, the output, in the time domain, is,

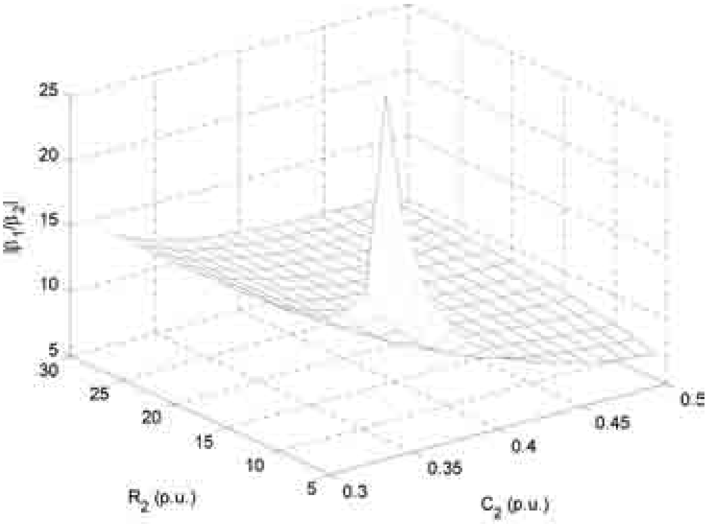
$$y(t)=\alpha\cdot u(t)+\beta_1e^{\lambda_1t}+\beta_2e^{\lambda_2t} \qquad (3.15)$$

where $\alpha=\frac{b_0c}{a_0}$; $u(t)$ is a unit step; $\lambda_1=\frac{-a_1+\sqrt{a_1^2-4a_2a_0}}{2a_2}$; $\lambda_2=\frac{-a_1-\sqrt{a_1^2-4a_2a_0}}{2a_2}$; $\beta_1=\frac{(b_1\lambda_1+b_0)c}{a_2(\lambda_1-\lambda_2)\lambda_1}$; $\beta_2=\frac{(b_1\lambda_2+b_0)c}{a_2(\lambda_2-\lambda_1)\lambda_2}$.

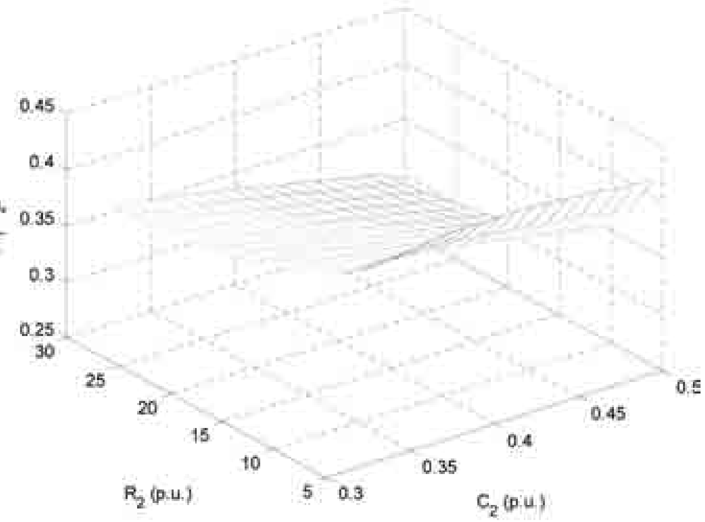
In Equation (3.15), a represents the magnitude of the steady-state rotor temperature; $\beta_1e^{\lambda_1t}$ and $\beta_2e^{\lambda_2t}$ correspond to rotor thermal transient.

Assuming that $R_1$ and $C_1$ are the bases for the thermal resistances and capacitances, respectively, i.e. $R_1$=1.0 p.u. and $C_1$=1.0 p.u., then according to the previous discussion, $R_2$=5.0~31 p.u., $R_3$=1.0~10 p.u., $C_2$=0.3~0.5 p.u.. By varying the values of $R_2$, $R_3$ and $C_2$ within their respective ranges, the ratios of $\beta_1$ to $\beta_2$ and $\lambda_1$ to $\lambda_2$ are obtained.

The change in $|\beta_1/\beta_2|$ with respect to the changes in $R_2$ and $C_2$ is plotted in Figure 3.4(a), while the change in $|\lambda_1/\lambda_2|$ with respect to the changes in $R_2$ and $C_2$ is plotted in Figure 3.4(b). Varying $R_3$ in conjunction with $R_2$ or $C_2$ yields similar results.



(a) Change in $|\beta_1/\beta_2|$ with respect to the changes in $R_2$ and $C_2$



(b) Change in $|\lambda_1/\lambda_2|$ with respect to the changes in $R_2$ and $C_2$

Figure 3.4: Identification of the dominant component in the rotor thermal transient.

As shown in Figure 3.4, $|\beta_1|$ is at least 6 times larger than $|\beta_2|$, and $|\lambda_1|$ is 30-45% of $|\lambda_2|$. These results indicate that $\beta_1e^{\lambda_1t}$ corresponds to a slow exponential change with large magnitude, while $\beta_2e^{\lambda_2t}$ corresponds to a fast but rather small thermal transient. Since the latter term vanishes quickly, $\beta_1e^{\lambda_1t}$ is identified as the dominant component in the rotor thermal transient. Similar conclusions can also be drawn for the stator thermal transient.

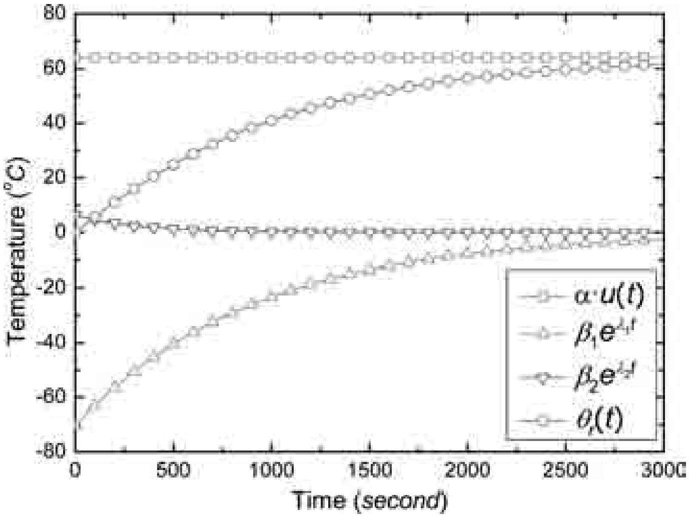


Figure 3.5: Different components in a typical rotor thermal transient.

With typical full order HTM parameters from [41], Figure 3.5 illustrates the simulation results of the rotor temperature rise at rated condition according to Equation (3.15). As shown in this figure, $\beta_2 e^{\lambda_2 t}$ decays to zero quickly, and the rotor thermal transient is captured chiefly by $\beta_1 e^{\lambda_1 t}$ Therefore, Equation (3.15) is simplified as,

$$y(t) \approx \alpha \cdot u(t) + \beta_1 e^{\lambda_1 t} = \alpha \cdot u(t) + \beta_1 e^{-\frac{t}{\tau_{th}}} \qquad (3.16)$$

where $\tau_{th}$ is the thermal time constant obtained from the rotor temperature, estimated by a parameter-based temperature estimator.

As a conclusion, the analysis of the HTM transfer function identifies $\beta_1 e^{\lambda_1 t}$ as the dominant component in the rotor thermal transient. It also associates the thermal time constant with $\lambda_1$ Simulations reveal that the stator winding thermal transient has the same thermal time constant as the rotor, which is the consequence of the strong correlation between the rotor and stator temperatures at running overload conditions.

### 3.2.1.2.3 THE ROLE OF $R_1$ IN THE HTM

Since a small to medium size induction motor's internal losses are dissipated chiefly through the stator to the ambient, the thermal resistance, $R_1$, is therefore the most significant factor in determining the steady-state rotor temperature and its thermal time constant in a rotor thermal transient. Due to the strong correlation between the rotor and stator temperatures, $R_1$ is also the most important factor in determining the steady-state stator temperature and its thermal time constant.

The steady-state stator winding temperature is formulated from Equation (3.9) as,

$$\theta_s(t)\Big|_{t=\infty} = \left(1 + \frac{KR'_2 - 1}{1 + R'_2 + R'_3}\right) R_1 c \qquad (3.17)$$

where $K$, $c$ and $R_1$ have the same definition as in the previous section; $R'_2$ is the ratio of $R_2$ to $R_1$, or the per unit value of $R_2$; similarly, $R'_3$ is the ratio of $R_3$ to $R_1$, or the per unit value of $R_3$.

By assigning $K$ and $c$ typical values at the rated condition [41] and varying $R'_2$ and $R'_3$ within their respective ranges, the simulation results of the steady-state stator winding temperature, $\theta_s(t)|_{t=\infty}$, are plotted in Figure 3.6. The results are normalized to the temperature at rated conditions.

As shown in Figure 3.6, the per unit change in $\theta_s(t)|_{t=\infty}$, due to the changes in $R'_2$ and $R'_3$ is between 0.8 and 1.0. Therefore, this fairly flat surface implies the lack of variations in $\theta_s(t)|_{t=\infty}$, with respect to the changes in $R_2$ and $R_3$. Compared with its insensitivity to $R_2$ and $R_3$, $\theta_s(t)|_{t=\infty}$, is in proportion to $R_1$ according to Equation (3.17). Such a phenomenon is explained by the fact that $R_1$ is directly connected to the stator side in the HTM, and that the motor's internal losses are dissipated chiefly through $R_1$.

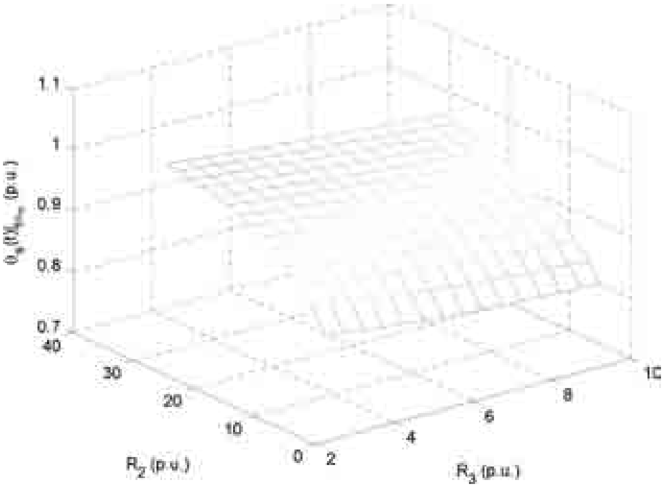
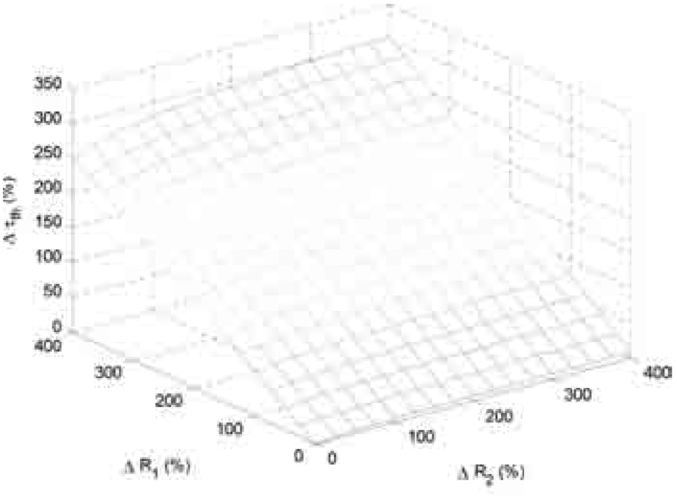
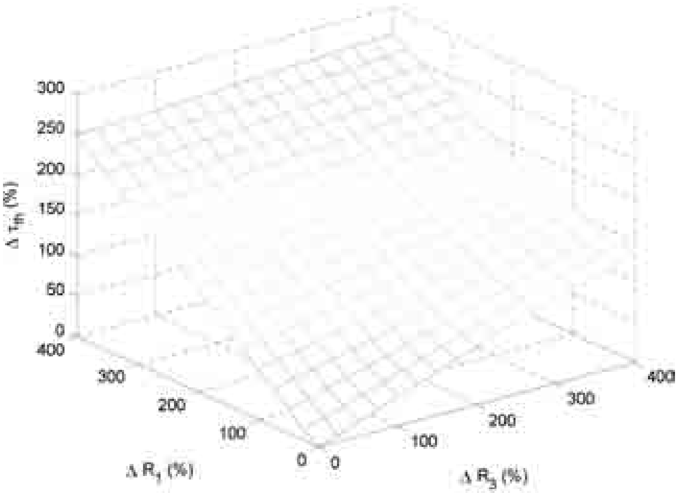


Figure 3.6: Normalized steady-state stator winding temperature.

Besides the significant influence that $R_1$ has on the steady-state stator winding temperature, it is also one of the most important factors in determining the thermal time constant in the stator thermal transient.



(a) Variations in $R_1$, $R_2$ and their effects on the thermal time constant



(b) Variations in $R_1$, $R_3$ and their effects on the thermal time constant

Figure 3.7: Effects of variations in $R_1$, $R_2$ and $R_3$ on $\tau_{th}$.

Figure 3.7 illustrates the variations in $R_1$, $R_2$ and $R_3$ and their effects on the thermal time constant. Both $R_1$ and $R_2$ are increased to 500% of their original values [41] to emulate the change of motor's cooling capability under impaired cooling conditions. The relative change in the thermal time constant, which is approximated by the negative reciprocal of $\lambda_1$, is plotted in Figure 3.7(a). Similarly, Figure 3.7(b) illustrates the relative change in the thermal time constant when $R_1$ and $R_3$ are increased.

Corresponding to an increase in $\Delta R_1$, marked increases in $\Delta\tau_{th}$ are observed in both Figure 3.7(a) and (b). In contrast to this, increments in $R_2$ and $R_3$ do not produce as significant changes in $\Delta\tau_{th}$ as $R_1$. In conclusion, $R_1$ is the dominant thermal parameter in determining the steady-state stator temperature, it is also critical to the thermal time constant in both the rotor and stator thermal transients.

### 3.2.2 REDUCED ORDER HYBRID THERMAL MODEL

As discussed in Section 3.2.1, induction machines with enclosures in the low power range are normally shielded by frames to provide basic protection against mild hazards, such as dust and moderate rain. Consequently, only a limited amount of air is exchanged between the inside and outside of the motor due to the enclosure, and hence the heat transfer by means of convection from the rotor directly to the external ambient, is restricted. In addition, this type of machine is also characterized by a small air gap (typically around 0.25-0.75 mm) to increase the efficiency [8]. Therefore, a significant portion of the heat caused by the rotor cage losses, is transferred across the air gap to the stator by means of laminar heat flow; while the remainder of the heat is passed to the endcap air inside the motor. The heat from the rotor cage losses, combined with the heat from the stator losses, travels through the stator frame and end shield and finally reaches the ambient [23]. In conclusion, the stator and rotor temperatures are highly correlated due to this heat flow pattern.

Since the internal heat of a small to medium size induction machine is dissipated chiefly through the stator to the ambient due to its design, the stator thermal properties in such a machine are the most significant factors in determining both the steady-state motor internal temperatures and the transient state motor thermal responses, as indicated in Section 3.2.1.2.3. The rotor thermal properties in such a machine, on the other hand, are usually insignificant compared to their stator counterparts [46]. Consequently, the rotor thermal properties can be replaced by a percentage of the heat flowing from the rotor to the stator. It is commonly assumed that 65% of the heat created by the rotor cage losses is transferred across the air gap at rated condition [26],[42].

From the above discussion, as well as the analysis presented in Section 3.2.1 for the full order hybrid thermal model, a reduced order hybrid thermal model with lumped thermal resistors and capacitor is proposed here for low-cost, small to medium size induction machines (Figure 3.8). This thermal model approximates the stator and rotor thermal characteristics, and the model parameters are loosely associated with various aspects of the machine design. By estimating the stator winding temperature rise above its ambient from only voltage and current measurements, the proposed thermal model safeguards the stator winding hot spot against excessive heating during the running overload conditions, where the stator current is between 100% and 200% of the motor's rated current.

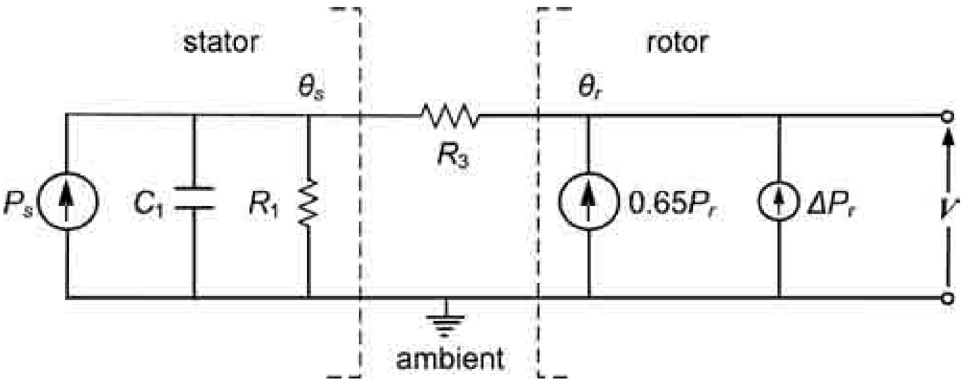


Figure 3.8: Reduced order hybrid thermal model for an induction motor.

As outlined before, approximately 65% of the heat created by the rotor cage losses is transferred across the air gap to the stator and ambient at rated speed. This figure may be different at other operating points. Therefore, $\Delta P_r$ is incorporated in the reduced order HTM to indicate the variation of the heat transferred from the rotor across the air gap to the stator at different load levels. The voltage, $V$, in Figure 3.8, represents the rotor conductor temperature rise observed from an induction machine parameter-based temperature estimator.

The hybrid thermal model correlates the stator winding temperature with the rotor conductor temperature by modeling their relationship with a thermal resistance, $R_3$, across the air gap. In addition, with the stator winding temperature estimated from the thermal model and the rotor conductor temperature estimated from the induction machine parameter-based temperature estimator, the hybrid thermal model also unifies the thermal model-based and the induction machine parameter-based temperature estimators. Furthermore, it has only three parameters, $R_1$, $R_3$ and $C_1$, that need to be determined. Simple offline tests similar to those described in reference [41] yield fairly accurate values for $R_1$, $R_3$ and $C_1$. After the successful identification of $R_1$, $R_3$ and $C_1$, an optimal estimate of the stator winding temperature can be obtained from an adaptive Kalman filter, which is constructed atop the hybrid thermal model.

### 3.3 SUMMARY

To track the stator winding temperature accurately and account for the disparities in thermal operating conditions for different motors of the same rating, this Section presents a hybrid thermal model for small to medium size induction machines with enclosures based on the analysis of induction machine thermal behaviors.

The induction machine thermal behavior is analyzed in Section 3.1. The analysis involves representing the induction machine thermal network with state-space equations and decomposing stator winding temperature rise collected from experimental data into different components. Induction machine thermal behaviors under different duty types are also discussed in this section.

Hybrid thermal models are proposed in Section 3.2 to correlate the voltage and current measurements to the stator winding temperatures. The model parameters are loosely associated with aspects of machine design and provide reasonable accuracy to the estimation of the stator winding temperature during induction machine operation with running overload. The hybrid thermal model utilizes the rotor resistance as an indicator of rotor temperature, and consequently the motor's thermal operating conditions. This model is therefore capable of reflecting the motor's true thermal characteristics, in an on-line fashion.

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# ARE BEARING CURRENTS CAUSING YOUR MOTOR FAILURES?

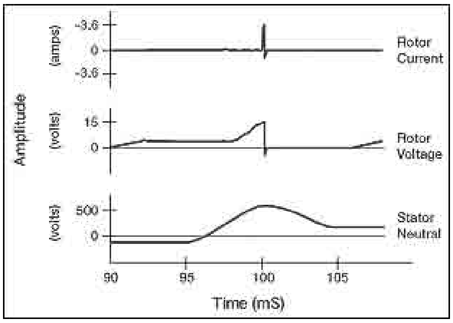
Greenheck

"We just lost another motor! Why are all of our motors failing?" Does this sound familiar? If you're at a loss to explain why your motors seem to experience premature failure one after another, take a step back and look at the big picture. Are all of the motors that have failed being controlled by variable frequency drives? If so, you may be experiencing the detrimental effects of shaft voltage resulting in bearing current.

What are they, why do they cause premature motor bearing failure, and how can you protect against them? To answer these questions, we first need to understand how variable frequency drives (VFDs, ADSs, or inverters) operate.

## VFD OPERATION

VFDs regulate the speed of a motor by converting sinusoidal line AC voltage to DC voltage, then back to a pulse width modulated (PWM) AC voltage of variable frequency. The switching frequency of these pulses ranges from 1 kHz up to 20 kHz and is referred to as the "carrier frequency".The ratio of change of the _V/_T creates a parasitic capacitance between the motor stator and the rotor, which induces a voltage on the rotor shaft. If this voltage, referred to as "common mode voltage" or "shaft voltage", builds up to a sufficient level, it can discharge to ground through the bearings. Current that finds its way to ground through the motor bearings in this manner is called "bearing current".



Example of voltage - current relationship

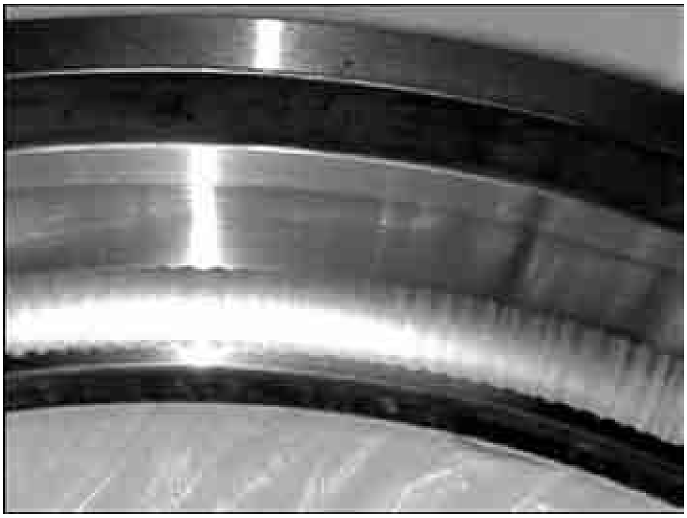
Let's examine how this condition develops, and what physically happens to the bearing as a result.

## BEARING DAMAGE

It should be noted that one of the major causes of bearing current results from voltage pulse overshoot created by the fast-switching IGBT (insulated gate bipolar transistor) in the VFD. We will discuss this phenomenon in the context of this publication. Other sources of shaft voltage include non-symmetry of the motor's magnetic circuit, supply unbalances, transient conditions, and others. Any of these conditions can occur independently or simultaneously to create bearing currents.

Shaft voltage accumulates on the rotor until it exceeds the dielectric capacity of the motor bearing lubricant, then the voltage discharges in a short pulse to ground through the bearing. After discharge, the voltage again accumulates on the shaft and the cycle repeats itself.

This random and frequent discharging has an electric discharge machining (EDM) effect, causing pitting of the bearing's rolling elements and raceways. Initially, these discharges create a "frosted" or "sandblasted" effect, and usually the first symptom of bearing current damage is the audible noise created by the rolling elements riding over these pits in the bearing race. Over time, this deterioration causes a groove pattern in the bearing race called "fluting" which is a sign that the bearing has sustained severe damage. Eventually, the deterioration will lead to complete bearing failure.



Bearing Fluting

## PROBLEM PREDICTION

VFD-induced shaft voltage can exist in every VFD-driven motor application. It is not specific to the air movement industry, nor is it specific to any particular manufacturer's motors, drives or equipment. However, shaft voltage only becomes a problem when it leads to bearing current and consequential damage to the motor bearings. How can you determine if your motor bearings are at risk? The truth is that the phenomenon of shaft voltages and bearing currents is well understood and well documented, but it is also somewhat rare and unpredictable.

The National Electrical Manufacturers Association (NEMA) Publication MG 1 Section IV "Performance Standards Applying to All Machines," Part 31 "Definite-Purpose Inverter-Fed Polyphase Motors" is the industry-accepted standard for defining what we call a VFD compatible motor. This standard addresses, in part, the motor's capability with respect to temperature, torque, insulation, and operating limitations (excess current, line voltage, across-the-line starting, etc). It also addresses "shaft voltages that can result in the flow of destructive currents through motor bearings", but concludes with the following statement:

"At this time, there has been no conclusive study that has served to quantify the relationship of peak voltage from inverter operation to bearing life or failure. There is also no standard method for measuring this voltage. Because of this, the potential for problems cannot consistently be determined in advance of motor installation."

Because of the phenomenon's rarity and unpredictability, most manufacturers do not include warnings or recommendations in their literature or operation and maintenance manuals.

## CONTRIBUTING FACTORS

Amidst the unpredictable cases of bearing current damage, industry experts have identified some things that exacerbate the occurrence and promote damaging effects:

### HIGH CARRIER FREQUENCY

The higher the carrier frequency, the higher the rate of the current discharge pulses, or the more rapid the damage caused by EDM will occur. At higher carrier frequencies the VFD will generally run quieter, however, it becomes more destructive on the motor insulation and bearings.

Most experts recommend that the carrier frequency be adjusted as low as possible without creating unacceptable audible noise levels, and to avoid frequencies above 6 kHz altogether. Accordingly, it is generally a good idea to specify and install a VFD that has an adjustable carrier frequency by relatively small increments (i.e. by 1 kHz increments) to allow for fine-tuning to the lowest acceptable level.

### CONSTANT SPEED OPERATION

Some industry experts believe that constant speed operation increases the risk of bearing current damage. Interestingly, the first well-known cases of bearing current damage were in clean room applications, in which VFDs controlled fan motors are used to maintain a constant airflow. However, there have been many cases of bearing current damage reported in air handling and other industry applications in which the equipment is not operating at a constant speed. While motor bearings operating at a constant speed are indeed more susceptible to EDM damage, motors that are in variable speed duties are certainly not immune.

### INADEQUATE GROUNDING

One of the largest potential causes of motor bearing damage due to bearing currents is inadequate grounding, especially at high operating frequencies. The challenge is to provide a low impedance ground path for the voltage to flow to earth ground without passing through the motor bearings or other components. Proper grounding is especially critical on the motor frame, between the motor and the VFD, and from the VFD to earth.

## PROBLEM IDENTIFICATION

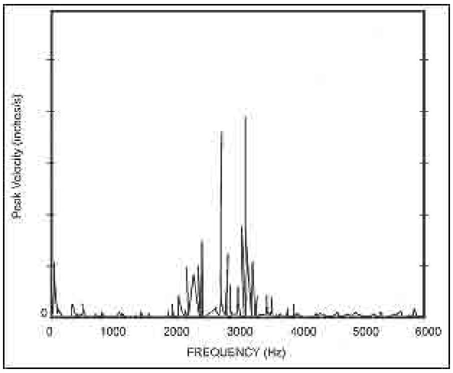
As stated earlier, the first symptom of bearing current damage is often the audible bearing noise. Unfortunately, by the time the bearing noise is apparent, EDM damage has already occurred and deterioration has developed to the point that complete bearing failure is probably not far behind.

Currently, there are two common non-destructive methods used in the industry to detect bearing currents and bearing current damage: vibration analysis, and shaft-to-ground voltage and current analysis. While both can be implemented to either confirm or deny bearing current suspicions, owners are better served by incorporating these methods to establish a baseline and monitor trends. This can provide early detection of possible problems. It can also verify whether or not any installed protection methods are effective.

It is important to understand that both of these test methods require very specialized equipment and experienced people to operate the equipment and analyze the data.

### VIBRATION ANALYSIS

Vibration analysis can be useful in confirming the existence of bearing fluting damage caused by EDM. The high frequency, high resolution spectrum of a bearing in the early stages of fluting damage will exhibit a "mound" of energy in the 2-4 kHz frequency range. As EDM damage continues and bearing degradation progresses, the fault energy spikes will migrate into regular bearing fault frequencies. Continuous monitoring of the vibration levels starting shortly after initial installation and start-up can provide important indications of increasing or changing energy spikes.



Example of vibration spectrum showing "Bearing Fluting"

### VOLTAGE ANALYSIS

Measuring the actual voltage and current present on the shaft can be helpful in determining the likelihood of damage from EDM. However, since all motors have some level of voltage, one must determine at what levels is cause for alarm. Unfortunately, there is no magic number that tells whether or not a motor is "safe" from EDM damage. For one thing, there are many variables that can affect the measured data, i.e., bearing lubrication, measurement equipment & method, running speed, etc. Additionally, this method of predicting EDM damage is not an exact science. Different experts have different opinions of "safe" levels depending on their individual experiences. Many experts, however, agree that trending this data can be most helpful in identifying deviations that can indicate the beginning of a problem, the worsening of an existing problem, or the failure of an EDM protection method.

## METHODS OF PROTECTION

Now that we understand how bearing currents are generated and what they can do to your motor bearings, as well as a couple of ways to determine whether or not there may be a problem, you're probably wondering how you can protect your motors.

Protecting motor bearings from an unpredictable occurrence of bearing currents is not an exact science, but rather a process of risk assessment and cost analysis. There are certain measures you can take in order to reduce the risks — but not without additional cost. Since the occurrences are unpredictable, one has to weigh the cost of protection against the costs in the event that the problem was to arise.

For example, installing a shaft grounding assembly in each of 15 direct-coupled fans with 100-HP motors would be much cheaper than replacing those 15 motors three months after start-up. On the other hand, replacing 15 smaller 3-HP motors would be much less expensive, so waiving the extra cost of shaft grounding assemblies might be an acceptable risk.

If protection is warranted, the following recommendations are a few of the most frequent that have been used successfully in various industries and applications.

### SHIELDED CABLE

High frequency grounding can be significantly improved by installing shielded cable with an extremely low impedance path between the VFD and the motor. One popular such cable type is continuous corrugated aluminum sheath cable. There are some new third party grounding kits that are just now becoming available to install as part of the whole system. Early testing and patent applications of such kits claim to eliminate common mode voltage from the system altogether.

Grounding Brush

### SHAFT GROUNDING

Grounding the shaft by installing a grounding device provides an alternate low-impedance path from the motor shaft to the motor case. This effectively channels the current away from the bearings. It significantly reduces shaft voltage, and therefore bearing current, by not allowing voltage to build up on the rotor.

One of the more popular shaft grounding devices is a grounding brush. Grounding brushes can be custom fit to virtually any motor shaft, and can also be retrofit to existing installations. They do, however, require replacement every few years depending on the shaft rotating speed, brush tension, and motor duty.

### INSULATED BEARINGS

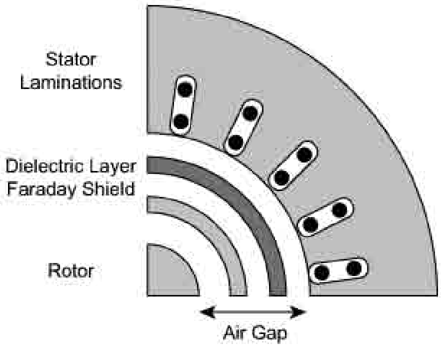
Insulated bearings eliminate the path to ground through the bearing for current to flow. But, installing insulated bearings does not eliminate the shaft voltage, which will still find the lowest impedance path to ground. This can potentially cause a problem if the path happens to be through the driven load or through some other component.

In order to direct the shaft voltage to ground through an acceptable path, one could install a shaftgrounding device in addition to the insulated bearings. Obviously this combination is better than one or the other independently, but at a much higher cost. Again, careful risk and cost analysis can help determine the extent of protection most appropriate for your situation. Insulated bearings tend to be rather expensive, and usually have substantial lead-times from suppliers.

Insulated Bearing

### FARADAY SHIELD

Placing grounded conductive material, such as copper foil tape or copper paint, in-between the rotor and the stator creates a Faraday Shield, resulting in an electrostatic shielded induction motor (ESIM). This method reduces the capacitively coupled currents crossing the motor air gap, minimizing the motor shaft voltage. One drawback to the Faraday shield is that the construction methods to obtain the desired benefits are very precise, which result in a higher cost motor.



Electrostatic Shielded Induction Motor (ESIM) with Faraday shield

## RESPONSIBILITY

Naturally, nobody wants to pay for repairs that follow damaging bearing currents if and when they do occur. And, spending extra money on protection methods for a problem that may or may not exist may be difficult to swallow in these days of tight budget considerations. Determining exactly where those responsibilities lie has been the topic of countless heated debates, many of which have resulted in costly litigation to settle the responsibility and cost issues.

After EDM damage occurs, some people contend that associated repairs fall within the jurisdiction of the motor warranty, while others claim that it's a warranty issue with the VFD manufacturer. To the contrary, it should not be considered as a warranty issue at all. A warranty claim implies a defect in material or workmanship. Bearing current damage can, and has, occurred in systems in which both the motors and drives were without defect.

During the early stages of a project, deciding if and how to implement protection methods is the ultimate responsibility of the owner. However, the system designers, engineers, equipment suppliers, and other players in the project are responsible for providing the owner with accurate and reliable information upon which an informed decision can be made.

Clearly, installing both the VFD and the motor from the same manufacturer narrows the number of parties involved, which would certainly make a responsibility debate easier; however, it does not necessarily prevent the situation from occurring in the first place. There are many factors outside the two individual components that can cause or promote bearing currents. For this reason, assigning ultimate accountability for a motor and VFD problem is difficult.

## RECOMMENDATIONS

The best way to protect yourself and your equipment is to understand the causes and effects of EDM damage in order to make informed decisions during the specification, requisition and installation stages. While there is no magic recipe to follow, in this article we offer some guidelines that at the very least will bring these issues to light for discussion and consideration.

## CONCLUSION

In contemplating these and other recommendations, it is important to carefully consider the entire system and all of the possible current paths. This is important both in trying to predict where problems would be most likely to occur, as well as identifying and correcting existing trouble areas.

Damaging bearing currents can occur in any VFD-controlled motor application, and will eventually cause catastrophic motor bearing failure. The motor bearings are damaged when accumulated shaft voltage discharges through the bearing causing an EDM effect. When and where bearing currents will become a problem is still unpredictable, although things such as high carrier frequency, constant speed operation and inadequate grounding can increase the risk and accelerate damage.

Suspicions of EDM damage can be verified by special vibration analysis techniques. Determining the likelihood of EDM damage in an existing application can be assisted by special voltage analysis to find possibly damaging current loops.

If bearing currents are a problem in your installation, or if the calculated risks are high enough, you can protect your equipment by using one of several methods, either independently or in combination. The most popular and successful methods include shaft grounding devices, insulated bearings, and Faraday shields.

Determining whether or not protection is warranted and determining the appropriate methods of protection is a shared responsibility based on cost analysis and risk assessment. Educating ourselves and each other about the cause, effect and protection of bearing currents is the best line of defense.

**Recommendations and guidelines**

| For· | Recommendation: | Notes |
|---|---|---|
| Every VFD Application | Set carrier frequency <6kHz | The lower the carrier frequency the better |
| | Specify VFD model with carrier frequency adjustability increments no larger than 1kHz | Fine tune to the lowest acceptable level |
| | Shortest possible conductor lengths | Reduces reflected wave current |
| | Shielded cable with continuous low-impedance ground path from the VFD to the motor | Various 3rd party grounding systems are immerging in the market |
| < 25 HP motor | Shaft grounding device | Some protection - requires maintenance |
| 25 HP & larger motor | Insulated motor bearings or ESIM | Higher level of protection |
| Long lead conductor | Inductive or RCL filter | Has to be individually tuned to the application |
| Difficult access to motor | Insulated motor bearings or ESIM | Higher level of protection - avoid high labor for motor replacement |
| Motor bearing failure despite protection | Voltage analysis to locate damaging current loops | Specialized equipment & personnel required |
| Noisy motor bearing operation | Vibration analysis to look for signs of EDM in motor bearings | Specialized equipment & personnel required |
| Failed motor bearing removed from motor | Inspect motor bearing races for signs of pitting or "fluting" | Qualified motor service technician required |

# MOTOR CONTROL

c3 Controls

## INTRODUCTION

The features, performance, and characteristics of today’s modern IEC (International Electrotechnical Commission) motor control devices provide users and specifiers many ways to reduce costs, improve performance, and enhance safety. This is different than in the past, when users and specifiers had a limited number of alternatives when selecting motor control devices for their applications.

## BACKGROUND

Before IEC motor control devices were readily available in the United States and Canada, users and specifiers typically selected traditional NEMA (National Electrical Manufacturers Association) motor control devices for their industrial applications. This selection generally included a contactor for controlling the motor (on/off), a thermal overload relay (typically eutectic alloy) for protecting the motor windings against overheating, or more commonly a starter (a factory assembly of a contactor and an overload relay). For short circuit protection of the motor branch circuit and its components – users and specifiers chose between a molded case circuit breaker or fuses, with the fuses typically installed on a disconnect switch. For installation convenience, users and specifiers might use a combination starter (an assembly of a contactor, thermal overload relay, and short circuit protective device – all factory wired in an enclosure). Combination starters often times included a control circuit transformer and pilot devices to actuate the motor controller and indicate the status (ex. on, off, tripped) of the devices.

The introduction of IEC motor control devices in the United States and Canada has provided users and specifiers with many more choices for their motor control requirements. In addition to IEC contactors and thermal overload relays, products such as motor protection circuit breakers that provide overload and short circuit protection in a single device are also available. The comparatively small size (to NEMA devices), advanced engineering materials, and operating principles of these devices have enabled users and specifiers to optimize the use of IEC motor control devices for each specific application.

This article will address installation codes and standards, industry solutions, product standards, and key considerations when selecting IEC motor control devices to help you reduce costs, improve performance, and enhance safety.

## INSTALLATION CODES AND STANDARDS

Before we discuss individual product features, characteristics, and performance – it is important to understand product installation codes and standards requirements that apply to motor control devices.

The purpose of the installation codes and standards is to prevent fires and catastrophic damage to equipment and facilities – ensuring a safe working environment for employees. Installation codes and standards are often times legal mandates, “users” must take care to comply with them.

### U.S. AND CANADA

In the United States, the primary installation codes of interest are:

- NFPA 70 – National Electrical Code (NEC)
- NFPA 79 – Electrical Standard for Industrial Machinery

In Canada, the primary installation code of interest is:

- CSA C22.1 – Canadian Electrical Code (CEC)

For motor branch circuits, the requirements of the NEC and CEC are very similar.

For simplicity, this paper will reference the NEC requirements.

Article 430, Motors, Motor Circuits, and Controllers of the NEC defines the requirements for all motor branch circuits. Every motor branch circuit must include components that provide the functions in Figure 1.

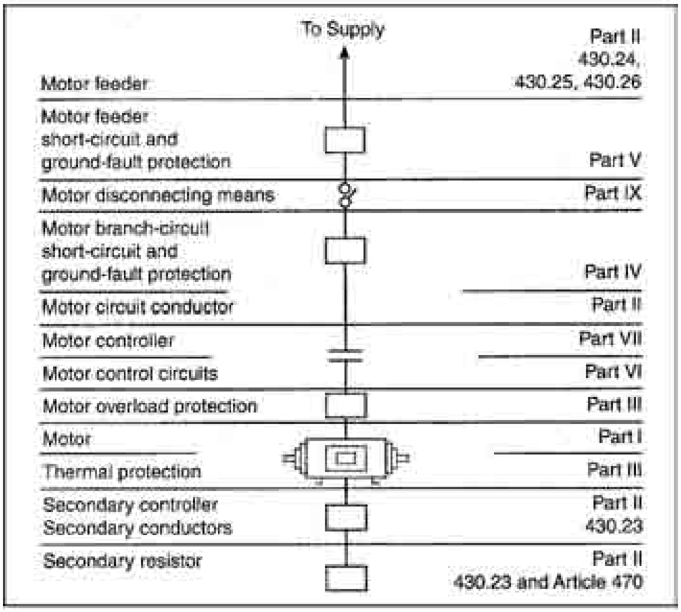


Figure 1

Typically, the functions identified in Figure 1 are performed by the following devices:

- Motor Disconnecting Means – Disconnect Switch, Molded Case Switch, or Molded Case Circuit Breaker
- Motor Branch-Circuit Short-Circuit and Ground Fault Protection – Molded Case Circuit Breaker or Fuses
- Motor Controller – Contactor

- Motor Overload Protection – Thermal Overload Relay

As will be addressed later in this paper, it is important to remember that all of the motor branch circuit functions must be provided – and that some devices are designed and optimized to perform one function (ex. a contactor for controlling) and other devices are designed and optimized to perform a different function. The newest motor control devices (ex. motor protection circuit breakers) provide multiple functions (control, overload protection, and short circuit protection).

### IEC

While the focus of this white paper is on the installation and application of IEC motor control devices in North America, for completeness – many countries have their own electrical codes and standards. In many of these countries, IEC standards are generally referenced. The primary installation codes of interest are:

- IEC 60204-1 – Safety of machinery – Electrical equipment of machines – General requirements
- IEC 60364 – Electrical Installations of Buildings

There are differences between the NFPA and IEC standards, but there are also many similarities – in fact activities are ongoing to harmonize NFPA 79 and IEC 60204-1.

A detailed comparison of these standards is beyond the scope of this article.

## INDUSTRY SOLUTIONS

The electrical industry has generally been considered to be very staid and conservative – without much change. In fact, quite the opposite is true – there have been a tremendous number of innovations and new products introduced, many of which provide real advantages and benefits to customers.

These innovations include electronic devices replacing electromechanical devices and circuit breaker devices replacing fuses. One change that many customers have adopted is the use of IEC motor control devices in place of NEMA motor control devices – primarily due to their smaller size and lower cost, but they also offer other features and benefits.

Following is a brief summary and comparison of the primary motor control devices that customers can choose from to control and protect their motors. Contactors and overload relays designed to meet NEMA, UL, and CSA standards and initially provided primarily for the North American market are called "traditional NEMA" devices. Contactors, overload relays, and motor protection circuit breakers designed to meet IEC and often times UL and CSA standards and initially provided primarily for markets outside of North America are called "traditional IEC" devices.

### MOTOR CONTROL DEVICES

**Contactors**

Definition: An electromechanical device that opens and closes a power circuit. Generally operated magnetically, providing remote control, but can also be operated manually. Power is controlled when the contactor's contacts open and close.

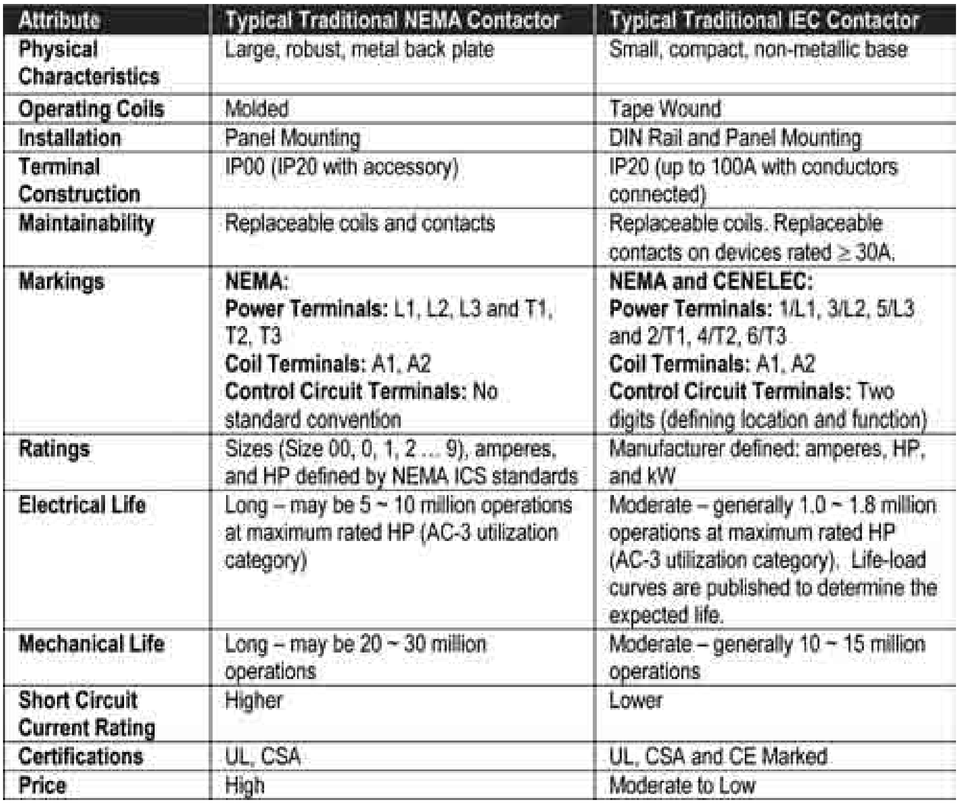
Function: To control motors (most common) and other power circuits (ex. transformers, heaters, lights, and capacitors).

There are two main types of contactors used in industrial applications – contactors designed to NEMA standards and contactors designed to IEC standards. Both types of devices can be used effectively, but they have different features, characteristics, and performance that sometimes make one better suited for a particular application than another.

Traditional NEMA contactors are designed to meet the size ratings (00, 0, 1, 2… 9) specified in NEMA standards. A NEMA contactor is designed by convention with sufficient reserve capacity to assure performance over a broad range of applications without the need for the specifier to assess the life requirements of the device.

Traditional IEC contactors are designed to match a contactor to a load, expressed in both the contactor's rating and expected life. IEC standards do not define standard sizes – the manufacturer can choose to apply any rating based on meeting the performance and test requirements of the IEC standards.

Table A is a comparison of the attributes of traditional IEC and NEMA contactors.



| Attribute | Typical Traditional NEMA Contactor | Typical Traditional IEC Contactor |
|---|---|---|
| **Physical Characteristics** | Large, robust, metal back plate | Small, compact, non-metallic base |
| **Operating Coils** | Molded | Tape Wound |
| **Installation** | Panel Mounting | DIN Rail and Panel Mounting |
| **Terminal Construction** | IP00 (IP20 with accessory) | IP20 (up to 100A with conductors connected) |
| **Maintainability** | Replaceable coils and contacts | Replaceable coils. Replaceable contacts on devices rated ≥ 30A. |
| **Markings** | **NEMA:**<br>**Power Terminals:** L1, L2, L3 and T1, T2, T3<br>**Coil Terminals:** A1, A2<br>**Control Circuit Terminals:** No standard convention | **NEMA and CENELEC:**<br>**Power Terminals:** 1/L1, 3/L2, 5/L3 and 2/T1, 4/T2, 6/T3<br>**Coil Terminals:** A1, A2<br>**Control Circuit Terminals:** Two digits (defining location and function) |
| **Ratings** | Sizes (Size 00, 0, 1, 2 … 9), amperes, and HP defined by NEMA ICS standards | Manufacturer defined: amperes, HP, and kW |
| **Electrical Life** | Long – may be 5 ~ 10 million operations at maximum rated HP (AC-3 utilization category) | Moderate – generally 1.0 ~ 1.8 million operations at maximum rated HP (AC-3 utilization category). Life-load curves are published to determine the expected life. |
| **Mechanical Life** | Long – may be 20 ~ 30 million operations | Moderate – generally 10 ~ 15 million operations |
| **Short Circuit Current Rating** | Higher | Lower |
| **Certifications** | UL, CSA | UL, CSA and CE Marked |
| **Price** | High | Moderate to Low |

Table A

For completeness, there are also solid-state contactors, vacuum contactors, mercury contactors, and definite purpose contactors that are also used in industrial and commercial applications – a detailed review of these devices is beyond the scope of this article.

### Thermal Overload Relays

Definition: Electromechanical device that prevents damage to a motor caused by excessive current. When an overload relay senses that a motor is overheating (ex. Drawing too much current over a specific period of time), the overload relay will trip, removing power to the motor (by interrupting the contact or coil circuit).

Function: To protect the windings of motors and the conductors to the motor against overload currents.

Traditional NEMA thermal overload relays typically accept interchangeable, field installable heater elements. Each overload relay will accept different heater elements based on the maximum current rating of the overload relay or the contactor size if the overload relay is to be directly installed on the contactor. The heater elements are typically eutectic alloy (although bimetal constructions are also available), and are indirectly heated. Heater elements are available with trip Classes 10, 20, and 30.

Traditional IEC thermal overload relays include integral, directly heated bimetal elements.

Typically these overload relays have an adjustable current setting, marked in amperes.

| Attribute | Typical Traditional NEMA Overload Relay | Typical Traditional IEC Overload Relay |
|---|---|---|
| Construction | Eutectic alloy (most common) or bimetal. Interchangeable heater elements. | Bimetal. Integral heater elements. |
| Trip Class | Class 10, 20 (most common), or 30 | Class 10 |
| Terminal Construction | IP00 (IP20 with accessory) | IP20 (with conductors connected) |
| Single Phase Sensitivity | No | Yes, provided by a differential mechanism |
| Reset Mode | Manual or Automatic (Bimetal) | Field Selectable Manual or Automatic |
| Current Setting | Fixed heater element (1:1.1 minimum to maximum current) | Adjustable current setting (1:1.5 minimum to maximum current) |
| Certifications | UL, CSA | UL, CSA and CE Marked |
| Price | High | Moderate to Low |

Table B

The minimum to maximum adjustment range is approximately 1:1.5 (ex. 10A to 15A).

Table B is a comparison of the attributes of traditional IEC and NEMA thermal overload relays.

For completeness, there are also electronic overload relays that actually measure current to the motor, as opposed to simulating the heating of the motor windings (ie. thermal overload relays) – a detailed review of these devices is beyond the scope of this article.

### Motor Protection Circuit Breakers

Definition: A circuit breaker that is assembled as an integral unit in a supporting and enclosing housing of insulating material. Thermal elements (various trip classes available, typically class 10) are ambient temperature compensated for precise overload protection of motor windings, and include phase loss protection.

Function: Motor Protection Circuit Breakers are multifunction devices designed to:

- Manually control motors (most common) and other power circuits (ex. transformers, heaters, and lights)
- Protect the windings of motors and the conductors to the motor against overload currents
- Protect motor circuit components (contactors, overload relays, and motors) and the conductors to the motor against short circuit currents
- Disconnect all of the motor circuit conductors simultaneously from their source of supply

Motor protection circuit breakers are designed to IEC standards – there is no equivalent NEMA motor protection circuit breaker or applicable NEMA product standard that applies to these devices, however, there are UL standards that these devices comply with.

The features, characteristics, and performance of IEC motor protection circuit breakers make them ideal for use in multi-motor applications, and more specifically "group motor installations". The benefits of utilizing motor protection circuit breakers in group motor installations is addressed in the Key Considerations section of this article.

Table C is a summary of the attributes of typical IEC motor protection circuit breakers.

### Assemblies

Rather than specifying components (contactors, overload relays, and motor protection circuit breakers), many users and specifiers purchase assemblies of these components.

These assemblies may be open style or in an enclosure. When enclosed, the assembly may include devices such as control circuit transformers, power supplies, push buttons, pilot lights, relays, fuses, disconnect switch-

| Attribute | Typical IEC Motor Protection Circuit Breaker |
|---|---|
| Physical Characteristics | Small, compact, non-metallic base. Integral bimetal thermal and magnetic or magnetic only trip mechanisms. |
| Terminal Construction | IP20 |
| Installation | DIN Rail and Panel Mounting |
| Markings | **NEMA and CENELEC:**<br>**Power Terminals:** 1/L1, 3/L2, 5/L3 and 2/T1, 4/T2, 6/T3<br>**Control Circuit Terminals:** Two digits (defining location and function) |
| Ratings | Manufacturer defined: amperes, HP, and kW |
| Electrical and Mechanical Life | 100,000 operations |
| Short Circuit Current Rating | 50kA at 460V |
| Trip Class | Class 10 |
| Single Phase Sensitivity | Yes |
| Reset Mode | Manual |
| Thermal Current Setting | Adjustable current setting (1:1.5 minimum to maximum current) |
| Magnetic Current Setting | Fixed, 12X maximum operating current. |
| Certifications | UL, CSA and CE Marked |

Table C

es, and molded case circuit breakers. NEMA devices have typically been supplied as factory assemblies, IEC devices are typically supplied as components for field assembly by the OEM, panel builder, or systems integrator. However, IEC devices are being supplied more frequently as assemblies today than in the past.

### SHORT CIRCUIT PROTECTIVE DEVICES

There are a number of choices of short circuit protective devices including fuses, molded case circuit breakers, and motor circuit protectors that a customer can choose to use.

Even though they are not "motor control devices" they are closely associated with and used with motor control devices. As described in the Installation Codes and Standards section of this paper, a short circuit protective device is required in every motor branch circuit. Details of each type of short circuit protective devices are beyond the scope of this article, however, following is a brief summary of these devices.

**Fuses**

Definition:

- An overcurrent protective device with a fusible link that operates (one-time only) to open the circuit on an overcurrent condition.

Function:

- Protect motor circuit components (contactors, overload relays, and motors) and the conductors to the motor against short circuit currents
- Protect the motor circuit conductors against overload currents

**Molded Case Circuit Breakers**

Definition: A device that is assembled as an integral unit in a supporting and enclosing housing of insulating material, designed to open and close a circuit by non-automatic means and to open the circuit automatically on a predetermined overcurrent (short circuit or overload), without injury to itself when properly applied within its rating.

Function:
- Protect motor circuit components (contactors, overload relays, and motors) and the conductors to the motor against short circuit currents
- Protect the motor circuit conductors against overload currents
- Disconnect all of the motor branch circuit conductors simultaneously from their source of supply

**Motor Circuit Protectors**

Definition:

- A device that is assembled as an integral unit in a supporting and enclosing housing of insulating material, designed to open and close a circuit by non-automatic means and to open the circuit automatically on a predetermined overcurrent (short circuit), without injury to itself when properly applied within its rating.

Function:

- Protect motor circuit components (contactors, overload relays, and motors) and the conductors to the motor against short circuit currents
- Disconnect all of the motor branch circuit conductors simultaneously from their source of supply
- In North America, motor circuit protectors can only be used when they are part of a listed combination motor controller where separate overload protection is provided

## PRODUCT STANDARDS

Manufacturers of industrial control devices take care to comply with product standards (as opposed to users being responsible for complying with installation codes and standards).

Product standards define device constructions, standard ratings, marking requirements, and test parameters and procedures to ensure that a device performs in accordance with its specified ratings.

Traditional NEMA motor control devices typically comply with NEMA, UL, and CSA product standards requirements. Many modern IEC motor control devices comply with IEC, UL, and CSA standards requirements. In addition, they may comply with other country specific standards (ex. VDE [Verband Deutscher Elektrotechniker] for Germany).

In general, there is nothing that prevents a manufacturer from claiming compliance with multiple standards. However, traditional IEC motor control devices typically do not comply with the applicable NEMA product standards.

The primary standards that are applicable to the motor control devices addressed in this paper are:

- UL 508, Industrial Control Equipment
- CSA C22.2 No. 14, Industrial Control Equipment
- NEMA ICS-1, Industrial Control Systems General Requirements
- NEMA ICS-2, Industrial Control Systems Controllers and Overload Relays

Rated 600V

- IEC 60947-1, Low-voltage switchgear and controlgear, Part 1:

General Rules

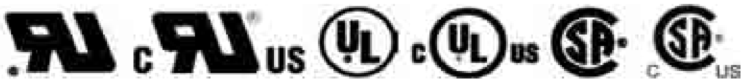
- IEC 60947-2, Low-voltage switchgear and controlgear, Part 2:

Circuit-breakers

- IEC 60947-4-1, Low-voltage switchgear and controlgear, Part 4-1:

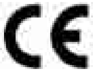
Electromechanical contactors and motor-starters

Third party certification and compliance with UL and CSA standards requirements is indicated by one or more of the following marks on the product and/or package:



There is no mark to indicate that a product complies with NEMA standards requirements.

Self-certified compliance with IEC standards requirements is typically indicated by the following mark on the product and/or package:



A complete listing of the applicable standards for the various motor control and short circuit protective devices addressed in this paper is included in Appendix 1.

## KEY CONSIDERATIONS

When selecting motor control devices for any application, there are a number of key considerations that will help you lower the total installed cost of your equipment over its entire life, maximize productivity, and enhance safety to personnel.

### IEC vs. NEMA

Both IEC and NEMA motor control devices can be used effectively in the most common motor control applications, however, knowing the features, performance, and characteristics of these devices (as summarized in Tables A, B, and C) will help you to choose the most appropriate product for each application. For OEMs, System Integrators, and Panel Builders that export equipment – NEMA motor control devices are generally not acceptable outside of the United States and Canada (exceptions include U.S. users such as Dow Chemical or General Motors, and others who sometimes duplicate manufacturing facilities throughout the world).

### Contactors

When selecting contactors for an application, key considerations include:

- Size
- Life
- Ease of installation
- Maintainability
- Price

For a given rating, IEC contactors are generally smaller than NEMA contactors, and may only require 20~30% of the panel area of a NEMA contactor. By using smaller contactors, control panel size can be reduced, and ultimately the overall size of the equipment can be reduced – all resulting in lower costs.

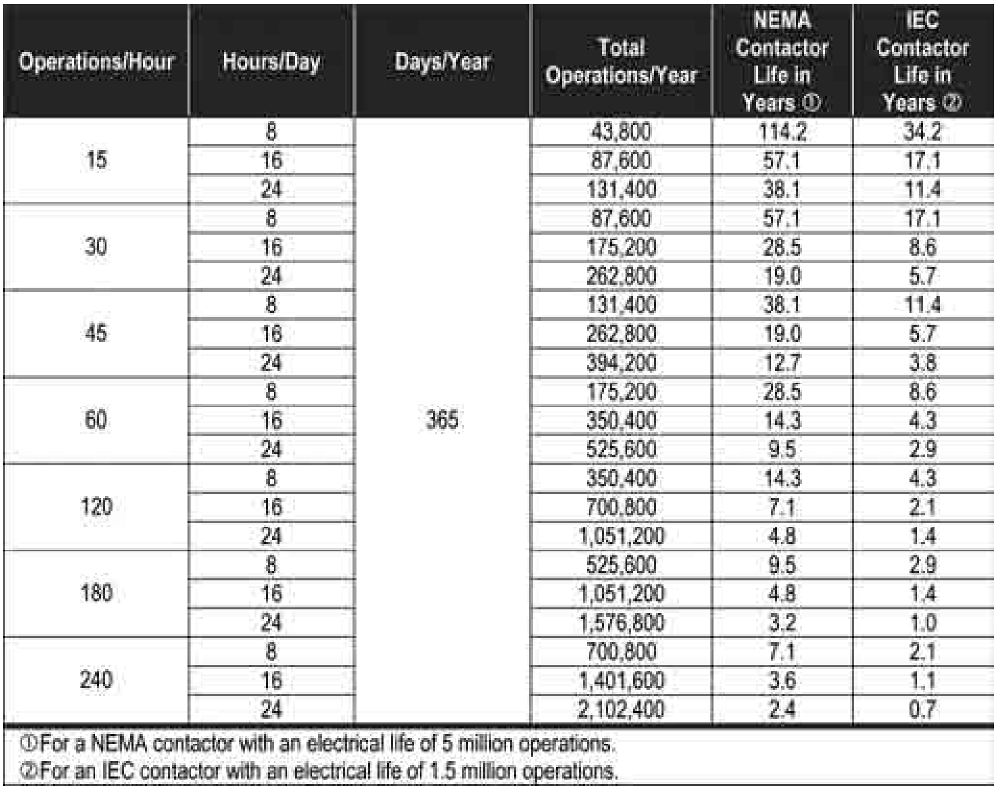
NEMA contactor designs have significant "reserve capacity" compared to IEC contactors which are rated more closely to their ultimate capacities. For example, a NEMA Size 1 contactor has a 10HP rating at 460V – which only requires a switching capability of 14A, however, the continuous current rating of a NEMA Size 1 contactor is 27A. In other words, a 100% safety factor. This safety factor results in an electrical life of up to 10 million operations of some NEMA contactors. In addition, the electrical life of NEMA contactors in various applications (ex. plugging, jogging, and normal starting and stopping of motors) is taken into consideration by the NEMA product standard when the NEMA size ratings were established – so the specifier doesn't need to consider electrical life when selecting a NEMA contactor (unless the duty is severe).

An IEC contactor with a 10HP rating at 460V (14A FLC) typically has a current rating of 16 ~ 18A, a 10 ~ 20% safety factor. The electrical life of an IEC contactor in this application is typically 1.2 ~ 1.5 million operations. In fact, most IEC devices rated up to 100A provide an electrical life of 1.0 ~ 1.8 million electrical operations. Because IEC contactors are rated closer to their ultimate capacities – the utilization category (ex. AC-3, AC-4) of the application must be considered to determine the electrical life of the contactor in the application. The electrical life of the contactor can be estimated with life-load curves published by the contactor manufacturer. See Appendix 2 for descriptions of typical utilization categories and an example of life-load curves.

Similarly, NEMA contactors are more robust than IEC contactors – housings are larger, contactors often include a metal base plate, and current carrying parts are larger which can result in a longer mechanical life compared to IEC contactors. The mechanical life of NEMA Size 0 to 3 contactors may be up to 30 million operations. Equivalently rated IEC contactors (9A to 100A) typically provide a mechanical life of 10 million to 15 million operations.

Therefore, when selecting an IEC or a NEMA contactor, electrical and mechanical life of the devices must be considered. When doing so, calculate the switching rate of the contactor in the application, and calculate the expected life of the contactor in the application.

See Table D, for a summary of switching rates and associated life in years – a switching rate of 45 ops/hr, 8 hrs/day, and 365 days/year will result in an IEC contactor life of 11.4 years and a NEMA contactor life of 38.1 years!



| Operations/Hour | Hours/Day | Days/Year | Total Operations/Year | NEMA Contactor Life in Years ① | IEC Contactor Life in Years ② |
|---|---|---|---|---|---|
| 15 | 8 | 365 | 43,800 | 114.2 | 34.2 |
| | 16 | | 87,600 | 57.1 | 17.1 |
| | 24 | | 131,400 | 38.1 | 11.4 |
| 30 | 8 | | 87,600 | 57.1 | 17.1 |
| | 16 | | 175,200 | 28.5 | 8.6 |
| | 24 | | 262,800 | 19.0 | 5.7 |
| 45 | 8 | | 131,400 | 38.1 | 11.4 |
| | 16 | | 262,800 | 19.0 | 5.7 |
| | 24 | | 394,200 | 12.7 | 3.8 |
| 60 | 8 | | 175,200 | 28.5 | 8.6 |
| | 16 | | 350,400 | 14.3 | 4.3 |
| | 24 | | 525,600 | 9.5 | 2.9 |
| 120 | 8 | | 350,400 | 14.3 | 4.3 |
| | 16 | | 700,800 | 7.1 | 2.1 |
| | 24 | | 1,051,200 | 4.8 | 1.4 |
| 180 | 8 | | 525,600 | 9.5 | 2.9 |
| | 16 | | 1,051,200 | 4.8 | 1.4 |
| | 24 | | 1,576,800 | 3.2 | 1.0 |
| 240 | 8 | | 700,800 | 7.1 | 2.1 |
| | 16 | | 1,401,600 | 3.6 | 1.1 |
| | 24 | | 2,102,400 | 2.4 | 0.7 |

①For a NEMA contactor with an electrical life of 5 million operations.
②For an IEC contactor with an electrical life of 1.5 million operations.

Table D

Depending on the number of contactors being installed in a control panel, ease of installation of the contactor can be extremely important. Most traditional NEMA contactors include metal base plates, the contactors are secured to a control panel with two to four screws.

If the control panel includes many contactors, a substantial amount of layout work (locating the fixing holes) and drilling and tapping of the fixing holes is required. All of these activities are labor intensive and increase the assembly cost of the control panel.

Typically IEC contactors rated up to 100A install on a standard DIN rail (as well as having the capability of being installed on a control panel with fixing screws). The contactor can be installed on the DIN rail without the use of tools – so many contactors can be installed very quickly. Layout is simplified and drilling and tapping are minimized because only a small number of fixing screws are required to secure the DIN rail to the control panel.

Therefore, installation and assembly costs can be reduced by taking advantage of the DIN rail installation feature of IEC contactors. In extremely high vibration and shock applications, securing the contactor to the control panel with fixing screws may be the best solution.

One of the main characteristics of NEMA contactors is their maintainability. Nearly all NEMA contactors (with the exception of some Size 00 contactors) offer replaceable operating coils and replacement contact kits. Contacts can be replaced when the contactor has reached the end of its electrical life.

IEC contactors also have replaceable coils, but many devices rated 30A or less are considered disposable and do not have replaceable contact kits. Typically, IEC devices rated above 30A (and 9A through 30A contactor from some manufacturers) have replacement contact kits to extend the electrical life of the contactor.

When considering replacing contacts, the cost of replacement of the entire contactor must be evaluated in comparison to the cost of replacement contacts and even more significantly, the cost of labor associated with changing the contacts.

Finally, for a given rating, an IEC contactor is generally less expensive than a NEMA contactor, and may only be 30~40% of the price of a NEMA contactor. The potential material cost savings of utilizing IEC contactors must be considered with the total installed cost (material, labor, maintenance, and replacement) over the life of the equipment in which the contactor is installed.

### Overload Relays

When selecting overload relays for an application, key considerations include:

- Trip class
- Eutectic alloy vs. bimetal design
- Adjustable current setting
- Single phase sensitivity
- Reset mode

The rating of an overload relay by "class" is an indication of how quickly an overload relay will trip during an overload condition (typically 6 ~ 10 times the motor full-load current).

According to IEC standards, Class 20 overload relays will trip within 20 seconds on an overcurrent that is 720% of the trip current setting and Class 10 overload relays will trip within 10 seconds on an overcurrent that is 720% of the trip current setting. See Appendix 3 for trip class definitions and time current curves.

NEMA-rated general-purpose motors generally have a greater mass than IEC-rated general-purpose motors (for a given power output), and are capable of withstanding overload currents for a longer period of time compared to IEC-rated motors. Therefore, NEMA-rated motors are adequately protected by Class 20 overload relays, the most common trip class for NEMA overload relays. IEC-rated motors are adequately protected by Class 10 overload relays, the most common trip class of IEC overload relays. However, some NEMA and IEC overload relays are also available in all trip classes (ex. Class 10, 20, and 30).

The motor acceleration time is an important criteria in the selection of the overload relay trip class – the overload relay trip time must permit the motor to attain its full rated speed, rated horsepower, and starting torque.

While Class 20 overload relays have typically been used to protect NEMA-rated motors,

Class 10 overload relays also protect NEMA-rated motors, and in actual applications, nuisance tripping of the overload relay is infrequent.

The construction of traditional NEMA overload relays includes interchangeable heater elements, most commonly the eutectic alloy type (also referred to as solder pot), but bimetal heater elements are also available. The construction of traditional IEC overload relays includes integral bimetal heater elements. Both IEC and NEMA overload relay constructions can provide effective protection to the motor. Eutectic alloy overload relay designs include a spring loaded ratchet mechanism that provides excellent performance and is resistant to nuisance tripping, particularly in high vibration and shock applications.

In the most common motor applications, bimetal overload relays also provide excellent performance, but their construction can be subject to nuisance tripping in high vibration and shock applications.

The adjustable current setting of IEC overload relays [a minimum to maximum setting range of 1:1.5 (ex. 10A to 15A)] provides users and specifiers flexibility during installation when the exact full load current of the motor is not known. The overload relay can be set to the exact motor full load current on sight, to ensure the motor is properly protected.

The interchangeable heater elements of NEMA overload relays have a very narrow current range [a minimum to maximum range of approximately 1:1.1 (ex. 10A to 11A)].

Ensuring proper protection requires that the exact overload relay heater element be available during installation. If the actual motor full load current were higher than expected, a heater element with a lower current rating would be subject to nuisance tripping.

If the actual motor full load current is lower than expected, a heater element with a higher current rating would not provide adequate protection to the motor against overload currents.

In addition to the protection provided by the two types of heater elements (integral and interchangeable), overload relays with integral adjustable heater elements enable OEMs, panel builders, and system integrators to reduce their inventories. Table E summarizes the typical number of overload relay (heater element) stock keeping units for NEMA contactors rated up to Size 3 and IEC contactors up to 100A.

| Range of Motor Full Load Currents | Number of NEMA Class 20 Eutectic Alloy Overload Relay Heater Elements | Number of IEC Class 10 Bimetal Overload Relays |
|---|---|---|
| 0.28A to 28A (Size 00 – 1) | 50 | 15 |
| 29A – 45A (Size 2) | 6 | 2 |
| 46A – 100A (Size 3) | 10 | 4 |

Table E

Phase loss conditions are one of the leading causes of damage to motors. In a phase loss condition (in a three phase system), the current in the remaining two phases increases to 173% of the normal motor running current.

IEC bimetal overload relays typically have a "differential mechanism" that causes the overload relay to trip faster under a phase loss condition, compared to the time it would take to trip when the overload relay is subjected to an overcurrent of 173%. Traditional NEMA overload relays generally do not have a differential mechanism, therefore, their response is slower to phase loss conditions than IEC overload relays.

Therefore, if phase loss conditions are common in a particular installation, IEC overload relays may provide the best protection, preventing damage to the motor due to phase loss and the significant expense of the motor repair or replacement.

Finally, the construction of IEC bimetal overload relays with integral heater elements enables overload relays to be provided that offer selectable manual or automatic reset modes. Automatic and manual reset is available with NEMA bimetal overload relays, but the reset mode is not field selectable, it must be factory ordered. NEMA eutectic alloy overload relays are available with manual reset only. While the NEC restricts the use of automatic reset overload relays (eg. in remotely installed equipment), IEC overload relays with bimetal elements and selectable reset mode provide greater application flexibility (and reduced inventory) compared to NEMA overload relays.

### Motor Protection Circuit Breakers

When selecting motor protection circuit breakers for an application, the only choice a specifier has is an IEC motor protection circuit breaker. A NEMA standard does not exist for these devices, nor do devices with "traditional NEMA motor control device features, performance, and characteristics" as defined in this paper exist. However, some users and specifiers may find some benefit in using an IEC motor protection circuit breaker in conjunction with a NEMA contactor.

The primary advantages that users and specifiers find in using IEC motor protection circuit breakers are as follows:

- Protective functions – overload and short circuit protection
- Single-phase sensitivity
- Compact size
- Modular design for use with IEC contactors
- Ease of installation – DIN rail mounting and a wide variety of wiring accessories

Features, performance, and characteristics of these devices aid in trouble-shooting, help with product optimization, and enhance safety. These benefits are described in the following section of this article.

### Trouble-Shooting

Trouble-shooting control panels is easier and faster as a result of the features provided by many IEC motor control devices. These features include status indication, advanced wiring accessories, DIN rail mounting, snap-on accessories, device markers, terminal markings, test functionality, fuseless short circuit protection, and modular component designs.

Status indication is provided by contactors, overload relays, and motor protection circuit breakers. Mechanical status indication on contactors is provided by the position of the contactor cross bar. Similarly, the operating knob of motor protection circuit breakers provides on/off indication as well as trip indication when the motor protection circuit breaker trips due to a short circuit or overload current. These mechanical indicators are obvious and intuitive for maintenance personnel servicing a control panel and are especially beneficial when there is a large number of devices in the control panel.

Identifying which devices are on, off, or tripped is quick and easy.

Status indication is also provided electrically by the change in state of auxiliary contacts of contactors, overload relays, and motor protection circuit breakers. Electrical status indication can be used to actuate HMI devices like indicating lights or tower lights, or as inputs to programmable logic controllers, I/O systems, and other industrial automation equipment.

Wiring errors are common in control panels. Advanced wiring accessories such as reversing contactor wiring modules, commoning links, feeder terminals, overload relay DIN rail/panel mount adapters, and contactor-circuit breaker link modules simplify and speed device wiring and installation and make wiring almost error-proof. Pre-formed wiring accessories ensure that the proper connections are made between the required terminals. Wiring errors are more frequent when individual conductors are cut, stripped, ends prepared, and then terminated in the devices.

When IEC motor control devices do need to be replaced, because they typically install on a DIN rail – they can be exchanged with a new device quickly and easily. Similarly, if during trouble-shooting, maintenance personnel believe a device may not be functioning properly, trying a new device is as simple as removing the device in question from the DIN rail, and snapping a new one in its place. Link modules and panel adapters also enable two or more devices to be assembled as a single unit and installed on a DIN rail or panel – speeding replacement.

A common feature of IEC motor control devices is snap-on accessories. Most IEC motor control devices have auxiliary contacts, interlocks, undervoltage release modules, shunt release modules, and other accessories that can be installed and removed without tools.

Therefore, when accessories have to be added to a device or replaced on a device, the process is fast and simple.

Another common feature of IEC motor control devices is integral device markers and terminal markings – providing users and specifiers with an easy means of identifying individual devices (ex. contactors, overload relays, motor protection circuit breakers, and auxiliary contacts) and terminals on those devices. These features are particularly useful when maintenance personnel are checking control panels and their wiring against a schematic diagram for the control panel.

Overload relays and motor protection circuit breakers also often times provide test functionality.

The test function of these devices causes their auxiliary contacts to change state and/or the mechanical status indicator to operate. This enables trouble-shooting personnel to check the functionality of the device without applying power. In addition, they can verify that the control circuit wiring is correct and that the control circuit indeed functions as desired.

Many IEC control panels take advantage of the fuseless short circuit protection functionality of motor protection circuit breakers. Because these devices provide visual status and trip indication, trouble-shooting after a fault has occurred can be much faster and easier than if fuses are used for short circuit protection. Unless an indicating fuse is used (that is more expensive than a non-indicating fuse), each fuse in a branch circuit must be metered and checked for continuity to determine which fuse must be replaced. Trouble-shooting after a fault is fast and easy with a motor protection circuit breaker. After the cause of the fault is identified and corrected, a motor protection circuit breaker can simply be reset and re-enabled.

If a fuse has blown, it must be removed, a replacement fuse found, and re-installed – taking more time and increasing maintenance and trouble-shooting costs. In reality, all fuses that have been subjected to a short circuit fault current should be replaced, even if they haven't blown – to reduce the likelihood of nuisance fuse blowing in the future. This also increases costs.

Finally, IEC motor control devices are modular in their design. They have standard dimensions, and are designed to be easily assembled and installed together – contactors with direct mounted overload relays, contactors with motor protection circuit breakers, and motor protection circuit breakers with contactors and overload relays.

The terminals and mechanical fixing features are specifically designed for simple and fast field assembly. In addition, accessories are typically shared across a broad range of devices (contactors in particular) – so if accessories do need to be replaced during trouble-shooting, it is more likely that the required accessory will be available.

**Product Optimization**

The ongoing evolution of IEC motor control devices has resulted in more sophisticated, and in many cases multi-function devices that have been optimized to perform specific functions (ie. disconnecting means, control, overload protection, and short circuit protection).

IEC contactors, overload relays, and motor protection circuit breakers have been optimized in their ratings, physical size, and modularity. As a result, equipment and machinery designs and performance can be optimized by the thoughtful selection and use of these products.

For a given range of motor horsepowers (ex. from 1HP to 75HP @ 460V) there are typically many more ratings of IEC contactors that a user or specifier can choose from compared to NEMA contactors. As you will recall, NEMA contactor ratings are defined by the NEMA standards with "Sizes" and IEC contactors can have any rating that the manufacturer assigns (provided the device meets the performance requirements specified in the applicable standard, ex. IEC 60947-4-1 for contactors). Because there are more ratings of IEC contactors, a user or specifier has a better opportunity to specify and purchase only as much contactor as is required for the application. As is shown in Table F below, there are only 5 NEMA contactors to cover applications from 1HP to 50HP at 460V, but there may be 9 IEC contactors available from a given manufacturer to cover the same horsepower range.

| HP @ 460V | NEMA Contactor Size | IEC Contactor Size |
|---|---|---|
| 1 | Size 00 | 9A |
| 2 | | |
| 5 | Size 0 | |
| 7.5 | Size 1 | 12A |
| 10 | | 18A |
| 15 | Size 2 | 25A |
| 20 | | 32A |
| 25 | | 40A |
| 30 | Size 3 | 50A |
| 40 | | 65A |
| 50 | | 80A |

Table F

Let's say that an application requires a contactor for a 15HP motor – if a NEMA device was being specified, a Size 2 contactor would be required. The Size 2 device has much greater capacity than is required for the application, it is capable of controlling a 25HP motor.

However, if an IEC contactor is selected, a 15HP device could be specified. What is the result of specifying an IEC contactor? A physically smaller, lower cost device.

As stated earlier, IEC contactors are rated much closer to the ultimate switching capabilities and have much less "reserve capacity" than their NEMA counterparts. This in great part contributes to the small physical size of IEC contactors compared to NEMA contactors (of the same horsepower rating). The design philosophy of IEC motor control devices was to use the minimum amount of materials necessary to achieve the desired performance. The basis for this philosophy lies in the origin of the design – Europe.

Because the availability of natural resources (ex. copper, silver, and plastics – petroleum based products) was scarce, it was only logical to make every effort to conserve these resources. This is in direct contrast to the United States where natural resources were abundant and therefore there was no need to conserve – adding extra material to devices provided excess capacity and better performance.

In addition to available resources, there was an emphasis on small size in Europe because there was less available land (again in comparison to the United States).

With less available land, making manufacturing plants and buildings smaller was achieved by making equipment and machines smaller, which was achieved by making motor control and other industrial control devices smaller.

Finally, the small size of IEC motor control devices can be attributed to modern design tools and techniques and the use of high performance engineering plastics and other materials. The designs of many IEC motor control devices are relatively new, in the last 10 to 15 years, in comparison to many NEMA motor control devices whose designs are 30 or more years old. Modern IEC motor control product designs have been developed, proven, and tested with the latest and greatest software, prototyping methods, advanced manufacturing and assembly processes.

The modular design of IEC motor control devices is well recognized. Virtually all devices install on the same mounting rail, a 35mm DIN rail. Virtually all 9A contactors, associated overload relays, and motor protection circuit breakers are 45mm wide – and have all been designed to be easily field assembled together. Similarly, common accessories (eg. auxiliary contacts) are generally shared between devices (particularly 9A to 100A contactors). These common dimensions, common mounting means, easy assembly, and shared accessories enable panel designs and assemblies to be standardized and optimized by using a variety of components that can be mixed-and-matched together to achieve the desired functionality and performance. Control panel designs can be automated and the design time as well as assembly time can be reduced – optimizing the specifying engineers and assemblers performance and productivity.

In addition to optimization as a result of ratings, small size, and modular designs, multi-function devices are replacing single function devices. Multi-function devices can optimize control panel and equipment design and assembly by reducing the total number of components in a panel and/or increasing the functionality (or improving the performance) of a machine without adding additional devices. Not only can the control panel be optimized, but inventory and stores can be reduced and optimized – with multi-function devices, it may be possible for an OEM, panel builder, or systems integrator to stock a single item instead of two or three different items.

One example of a multi-function device is an IEC bimetal overload relay with manual and automatic reset. Because the relay provides a selectable reset mode, it isn't necessary for an OEM, panel builder, or systems integrator to stock both manual reset overload relays and automatic reset overload relays in every current rating. As an example, if there are 15 different overload relays to cover a range of full load currents from 0.28A to 32A, 15 fewer stock keeping units (SKUs) can be inventoried as a result of the overload relay providing selectable manual or automatic reset – 30 SKUs would have to be stocked if manual and automatic reset were offered in different devices.

The IEC motor protection circuit breaker is a second example of a multi-function device – it provides four different functions: disconnecting means, control, overload protection, and short circuit protection. It has the capability to replace four different devices that might be found in a traditional control panel. The functions and performance of the motor protection circuit breaker make it ideal for use in multi-motor applications – specifically group motor applications in North America. The requirements for multi-motor applications are defined in Article 430-53 of the NEC. A group motor installation with IEC motor protection circuit breakers is one of the best examples of optimization resulting from the use of IEC motor control devices.

By taking advantage of the motor protection circuit breaker's functions, performance, and associated accessories:

- control panel size can be reduced, and
- control panel wiring can be reduced both of which reduce installation time and ultimately the total installed cost of the control panel.

Eliminating single function devices like fuses and overload relays and replacing them with motor protection circuit breakers can reduce the control panel size by 50% or more.

The enclosure is a significant portion of a control panel's cost, so by reducing the enclosure size from 24" x 24" to 20" x 12", the total cost of the control panel can be reduced substantially.

Figures 2 and 3 are graphical representations of a Traditional Multi-motor Application and a Group Motor Application that takes advantage of a motor protection circuit breaker and the benefits realized by replacing fuses or molded case circuit breakers and overload relays.

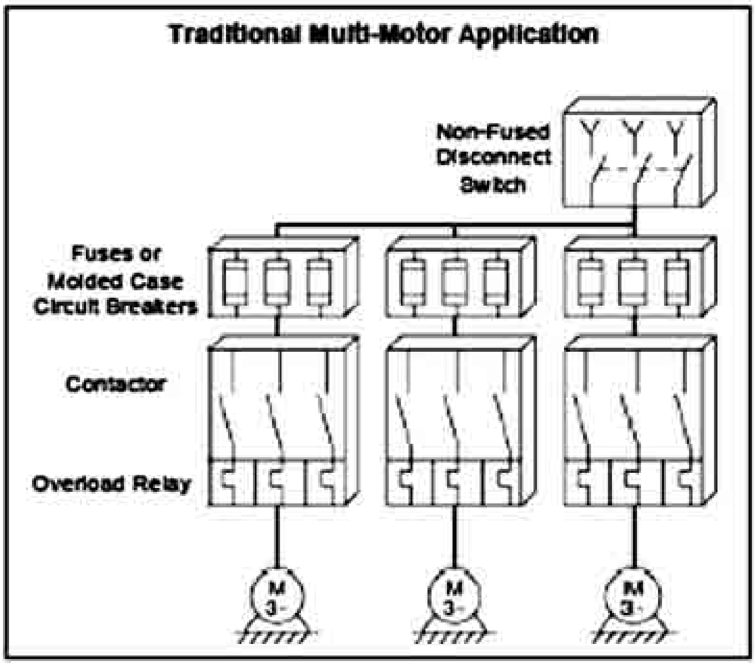

Traditional Multi-Motor Application
Non-Fused Disconnect Switch
Fuses or Molded Case Circuit Breakers
Contactor
Overload Relay
M 3~
M 3~
M 3~

Figure 2

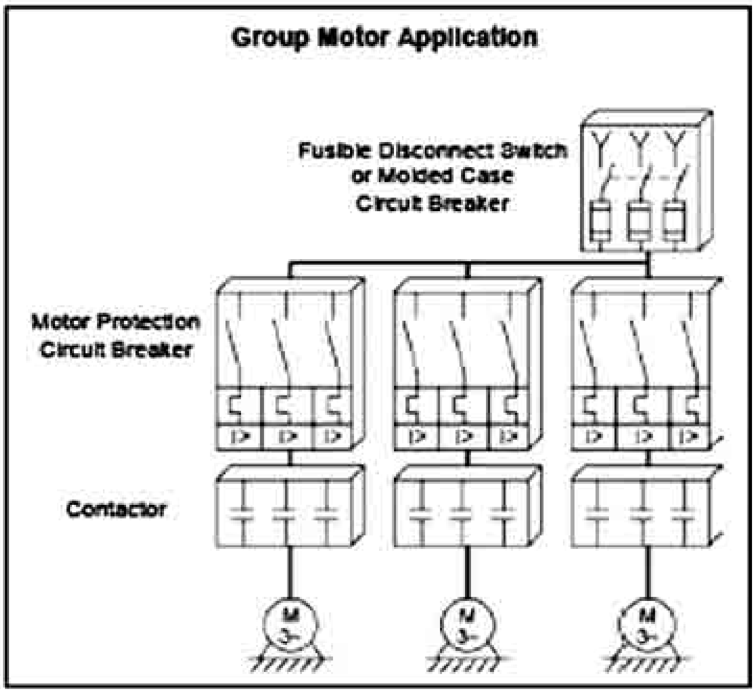

Group Motor Application
Fusible Disconnect Switch or Molded Case Circuit Breaker
Motor Protection Circuit Breaker
Contactor
M 3~
M 3~
M 3~

Figure 3

Utilizing wiring accessories such as commoning links and feeder terminals that are generally offered with motor protection circuit breakers reduces control panel wiring. The use of these accessories minimizes point-to-point wiring and dramatically reduces the time to cut and prepare individual conductors for electrical connections between individual single function devices (eg. from a fuse block to a contactor). The use of wiring accessories has enabled some OEMs, panel builders, and systems integrators to reduce their wiring time by as much as 30~35%. In addition to reducing the wiring time, wiring errors can be significantly reduced because the wiring accessories are specifically designed for error-proof installation.

Finally, total installed costs can be reduced by eliminating a significant number of drilling and tapping operations because IEC motor control devices and assemblies can be easily and quickly installed on a standard 35mm DIN rail which in many cases can be firmly secured to the enclosure mounting plate with only two screws.

If the use of motor protection circuit breakers in multimotor installations to reduce total installed costs isn't enough reason to consider using them, then consider the following device features that can enhance the performance and functionality of a control panel:

- Visual trip indication – to simplify trouble-shooting
- Operators can be padlocked OFF – to enable servicing of individual branch circuits
- IP20 Guarded terminals – to prevent accidental contact with live parts
- Type 2 Short Circuit Coordination at fault levels up to 50kA
- Phase loss sensitivity – to protect motors against damaging single-phase conditions

**Enhanced Safety**

Safety to personnel is one of the most important if not the most important consideration when selecting motor control devices for an application. Two characteristics of IEC motor control devices that specifically contribute to enhanced safety are IP20 guarded terminals and Type 2 Short Circuit Coordination. Some NEMA motor control devices also offer IP20 guarded terminals (sometimes with an add-on accessory) and Type 2 Short Circuit Coordination, but these features are more commonly recognized as being associated with IEC motor control devices.

IP20 guarded terminals prevent accidental contact with live parts. To meet IP20 requirements, a 12.5mm (1/2") solid object must not be able to contact a "live" terminal of a device (see Appendix 4 for a complete overview of the various ingress protection ratings defined in IEC 60529). This provides enhanced safety to maintenance personnel when they are trouble-shooting a panel that is "live" (even though this is not a recommended practice). Maintenance personnel can take current measurements, check the secureness of the terminal, and perform other trouble-shooting activities with a minimum risk of electric shock.

Type 2 Coordination means that a starter will not be damaged in the event of a short circuit fault. Following is the definition of Type 2 Coordination from IEC 60947-4-1:

Type 2 Coordination: under short-circuit conditions, the contactor or starter shall cause no danger to persons or installation and shall be suitable for further use. The risk of contact welding is recognized, in which case the manufacturer shall indicate the measures to be taken with regard to the maintenance of the equipment.

Most users and specifiers believe motor control devices that are UL Listed or CSA Certified automatically provide this level of protection for a starter – but that is not the case. Starters may be damaged after some UL/CSA short circuit tests, in these cases acceptable test results are similar to IEC Type 1 Coordination:

Type 1 Coordination: under short-circuit conditions, the contactor or starter shall cause no danger to persons or installation and may not be suitable for further service without repair and replacement of parts.

By specifying Type 2 Coordination, safety to personnel is enhanced because arc flashes resulting from short circuit faults can be eliminated. Arc flashes can release tremendous energy in a very short period of time. Hot metal can be discharged from the equipment and metal parts can even be vaporized. The thermal energy released from the arc flash can result in severe burns to workers. Finally, arc flashes can create loud explosions and tremendous pressures that can result in ruptured eardrums, collapsed lungs, and forces that can violently knock workers off their feet or from a ladder. The potential for injury can be minimized if control panel enclosure doors are always kept closed, but this isn't always possible.

In addition to enhanced safety, Type 2 Coordination provides the following benefits:

- Reduced component replacement costs
- Increased productivity
- Simple device selection

Component replacement costs are reduced because contactors, starters, and motor protection circuit breakers are protected against damage – so they don't need to be repaired or replaced after a short circuit fault.

Productivity is also increased because contactors, starters, and motor protection circuit breakers are protected against damage due to the short circuit. Downtime is reduced because there is no need to repair or replace any damaged components.

Also, it is simple to select the appropriate motor control devices that provide Type 2 Coordination – manufacturers provide easy to use tables that match the motor protection circuit breaker and contactor that will provide Type 2 coordination up to a specified short circuit fault current. See Appendix 5 for an example of a typical table. Motor protection circuit breaker and contactor combinations are the easiest to select – in most cases they have been designed to function properly together to achieve Type 2 Coordination.

Type 2 Coordination can also be achieved with contactors, overload relays, fuses, and some molded case circuit breakers – but the selection of the components is a little more difficult as system electrical design, the let-through currents and let-through energies of the short circuit protective devices (fuses and molded case circuit breakers), and the withstand capability of the motor control devices must be considered.

Finally, third-party certifications are a final assurance that products comply with relevant safety standards, ensuring that the product is found to be free from reasonably foreseeable risk of fire, electric shock and related hazards. Typical third party certifications are indicated by markings applied to the product and/or package as described in the Product Standards section of this article.

CE marking is a European marking of conformity that indicates that a product complies with the essential requirements of the applicable European laws or Directives with respect to safety, health, environment and consumer protection. Generally, this conformity to the applicable directives is done through self-declaration. The CE Mark provides a means for a manufacturer to demonstrate that his product complies with a common set of laws and the applicable standards (as specified by the manufacturer) for the product.

## CONCLUSION

Each and every specifier and user wants to reduce costs, improve performance of their machines and equipment, and enhance the safety of personnel in their facilities. Utilizing IEC motor control devices is one way to help achieve those objectives. Realize your business objectives through the thoughtful evaluation and selection of these devices.

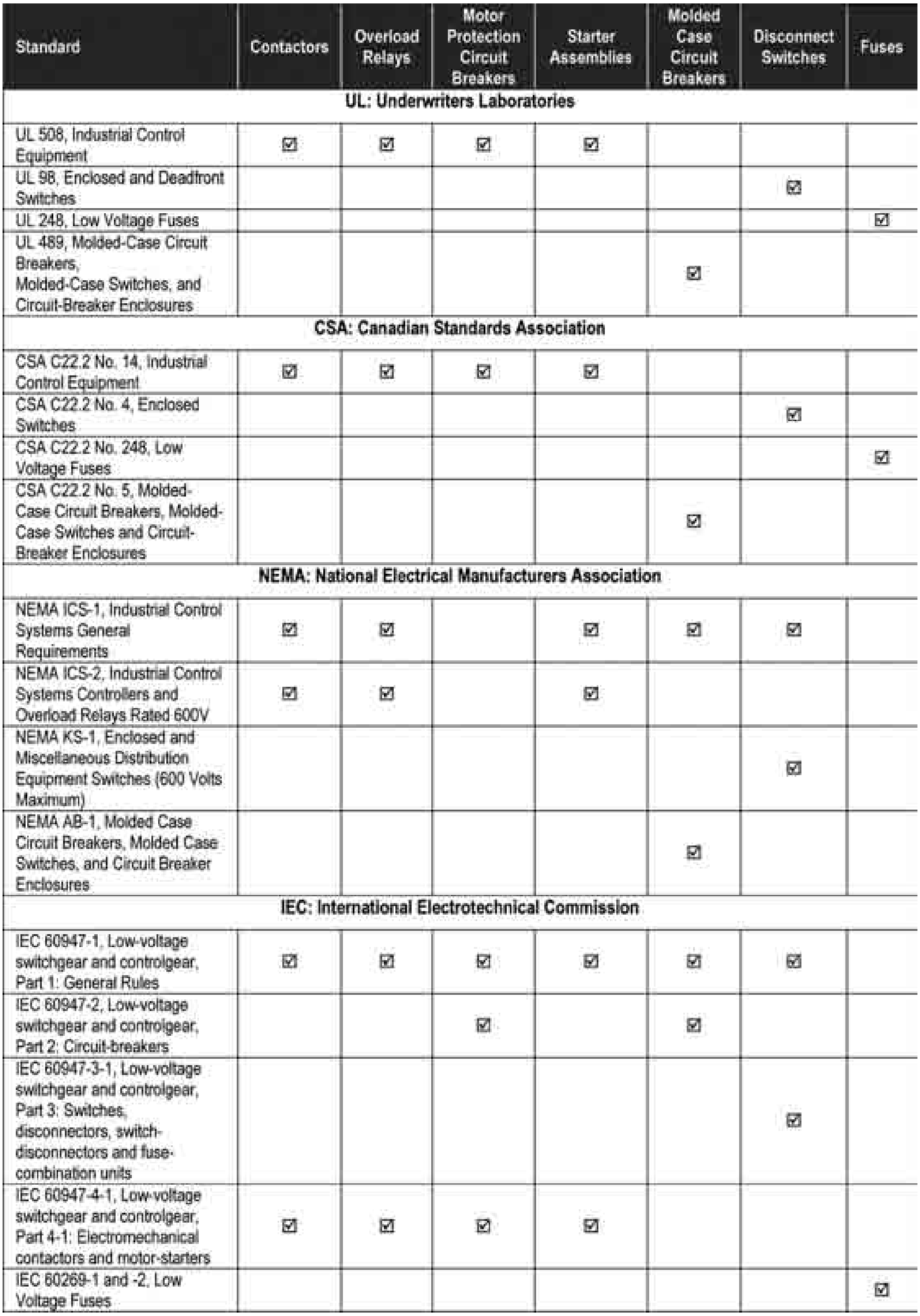
As this paper has demonstrated, customers have many choices and there are a number of key considerations when selecting and specifying motor control devices. These considerations include:

- NEMA vs. IEC
- Trouble-shooting
- Product optimization
- Enhanced safety

In conjunction with these key considerations and IEC motor control device characteristics, evaluate installation code requirements and product standards compliance.

The features of IEC contactors, overload relays, motor protection circuit breakers, and assemblies of those components are abundant, their characteristics and specifications make them ideally suited to reduce costs, improve performance, and enhance safety.

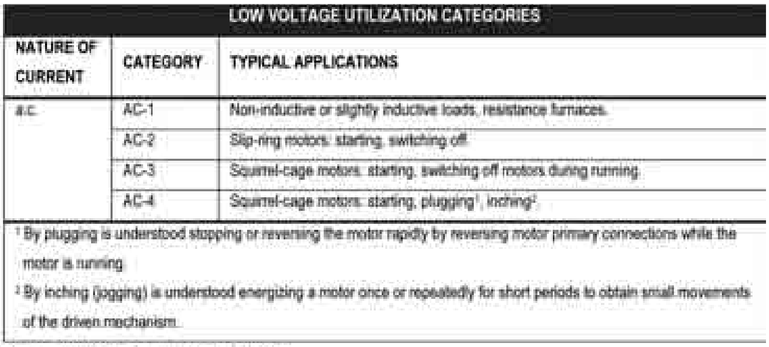
## APPENDIX 1 – PRODUCT STANDARDS



| Standard | Contactors | Overload Relays | Motor Protection Circuit Breakers | Starter Assemblies | Molded Case Circuit Breakers | Disconnect Switches | Fuses |
|---|---|---|---|---|---|---|---|
| **UL: Underwriters Laboratories** | | | | | | | |
| UL 508, Industrial Control Equipment | ☑ | ☑ | ☑ | ☑ | | | |
| UL 98, Enclosed and Deadfront Switches | | | | | | ☑ | |
| UL 248, Low Voltage Fuses | | | | | | | ☑ |
| UL 489, Molded-Case Circuit Breakers,<br>Molded-Case Switches, and Circuit-Breaker Enclosures | | | | | ☑ | | |
| **CSA: Canadian Standards Association** | | | | | | | |
| CSA C22.2 No. 14, Industrial Control Equipment | ☑ | ☑ | ☑ | ☑ | | | |
| CSA C22.2 No. 4, Enclosed Switches | | | | | | ☑ | |
| CSA C22.2 No. 248, Low Voltage Fuses | | | | | | | ☑ |
| CSA C22.2 No. 5, Molded-Case Circuit Breakers, Molded-Case Switches and Circuit-Breaker Enclosures | | | | | ☑ | | |
| **NEMA: National Electrical Manufacturers Association** | | | | | | | |
| NEMA ICS-1, Industrial Control Systems General Requirements | ☑ | ☑ | | ☑ | ☑ | ☑ | |
| NEMA ICS-2, Industrial Control Systems Controllers and Overload Relays Rated 600V | ☑ | ☑ | | ☑ | | | |
| NEMA KS-1, Enclosed and Miscellaneous Distribution Equipment Switches (600 Volts Maximum) | | | | | | ☑ | |
| NEMA AB-1, Molded Case Circuit Breakers, Molded Case Switches, and Circuit Breaker Enclosures | | | | | ☑ | | |
| **IEC: International Electrotechnical Commission** | | | | | | | |
| IEC 60947-1, Low-voltage switchgear and controlgear, Part 1: General Rules | ☑ | ☑ | ☑ | ☑ | ☑ | ☑ | |
| IEC 60947-2, Low-voltage switchgear and controlgear, Part 2: Circuit-breakers | | | ☑ | | ☑ | | |
| IEC 60947-3-1, Low-voltage switchgear and controlgear, Part 3: Switches, disconnectors, switch-disconnectors and fuse-combination units | | | | | | ☑ | |
| IEC 60947-4-1, Low-voltage switchgear and controlgear, Part 4-1: Electromechanical contactors and motor-starters | ☑ | ☑ | ☑ | ☑ | | | |
| IEC 60269-1 and -2, Low Voltage Fuses | | | | | | | ☑ |

## APPENDIX 2 – UTILIZATION CATEGORIES AND LIFE-LOAD CURVES

### Utilization Categories



| LOW VOLTAGE UTILIZATION CATEGORIES | | |
|---|---|---|
| NATURE OF CURRENT | CATEGORY | TYPICAL APPLICATIONS |
| a.c. | AC-1 | Non-inductive or slightly inductive loads, resistance furnaces. |
| | AC-2 | Slip-ring motors: starting, switching off |
| | AC-3 | Squirrel-cage motors: starting, switching off motors during running. |
| | AC-4 | Squirrel-cage motors: starting, plugging[1], inching[2] |

[1] By plugging is understood stopping or reversing the motor rapidly by reversing motor primary connections while the motor is running.

[2] By inching (jogging) is understood energizing a motor once or repeatedly for short periods to obtain small movements of the driven mechanism.

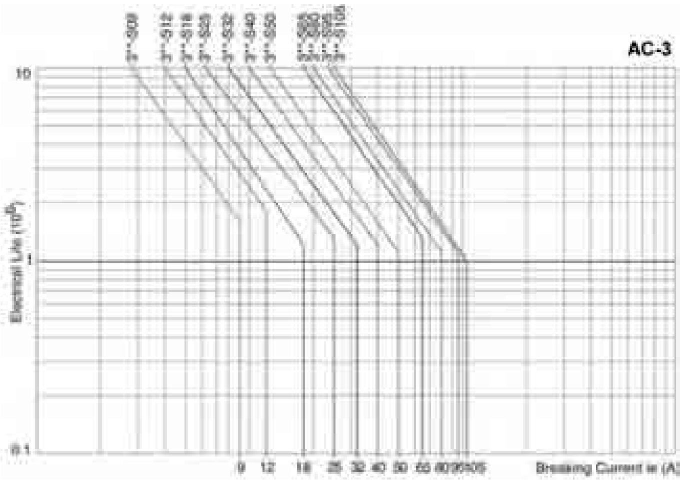
Source: ©International Electrotechnical Commission

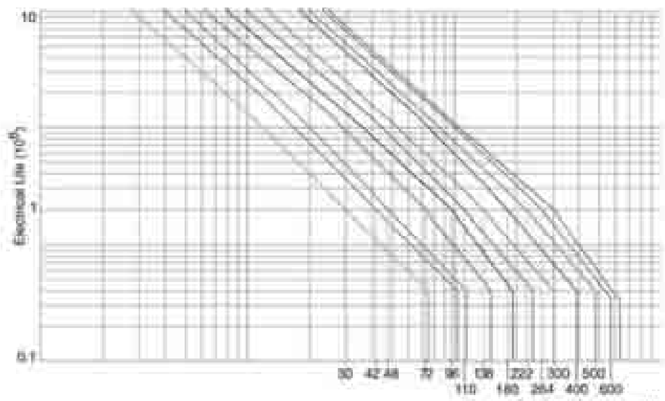
### ELECTRICAL LIFE IN UTILIZATION CATEGORY

To find a contactor's estimated life:

1. Identify the utilization category of the application.
2. Refer to the chart for the applicable utilization category.
3. Locate the intersection of the life-load curve for the contactor selected with the application breaking current (Ie) on the horizontal axis of the chart.
4. Read the estimated contactor life from the vertical axis of the chart.

The life-load curves are based on tests in accordance with IEC 60947-4-1. Many conditions of an actual application effect contact life such as the environment and duty cycle, therefore, the actual contact life may vary from the life indicated by the curves shown here.





## APPENDIX 3 – TRIP CLASSES AND TIME CURRENT CURVES

### Trip Classes

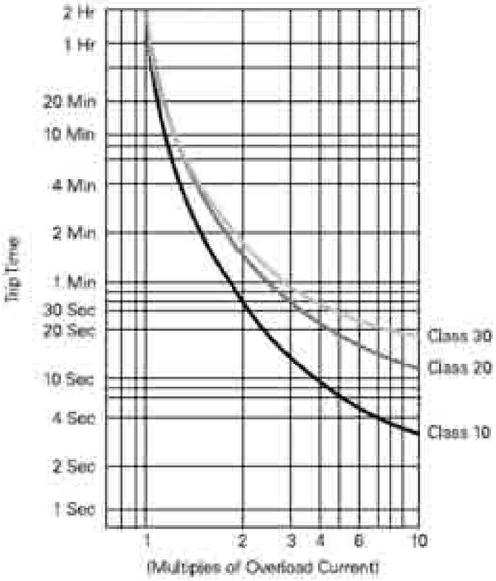
Class 10: The overload relay will trip within 10 seconds when carrying a current of 720% of the current setting.

Class 20: The overload relay will trip within 20 seconds when carrying a current of 720% of the current setting.

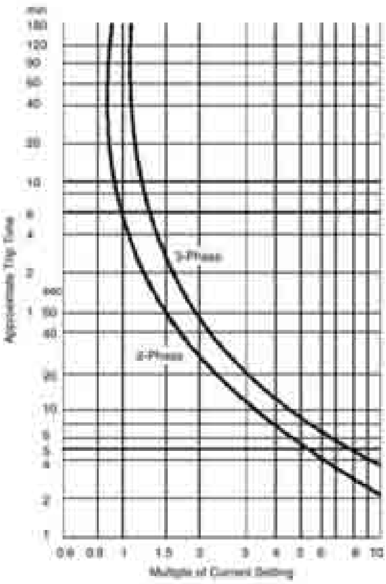
Class 30: The overload relay will trip within 30 seconds when carrying a current of 720% of the current setting.

### Time Current Curves

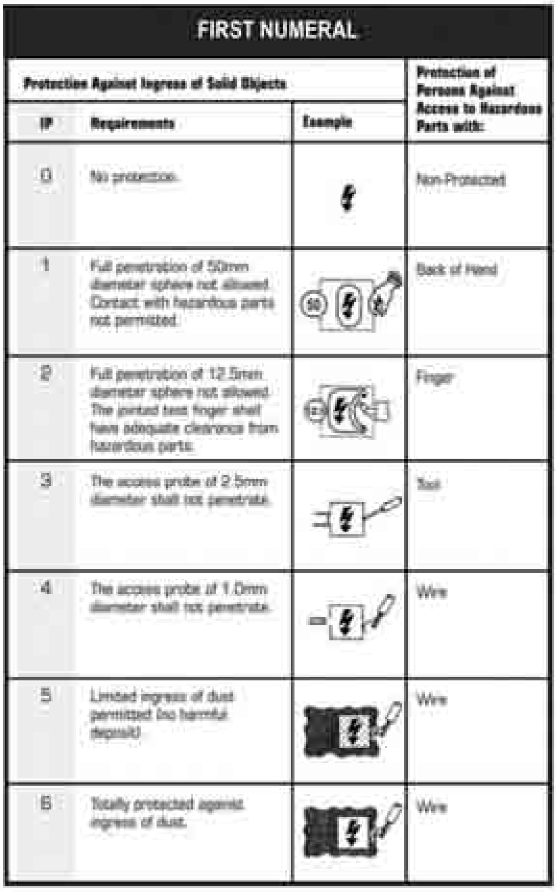
**Typical Time – Current Curves by Trip Class**



**IEC Bimetal Overload Relay with Differential Trip Mechanism**

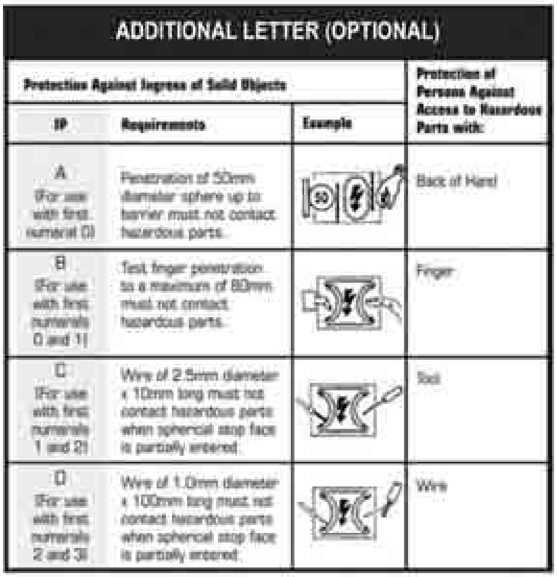


## APPENDIX 4 – INGRESS PROTECTION RATINGS



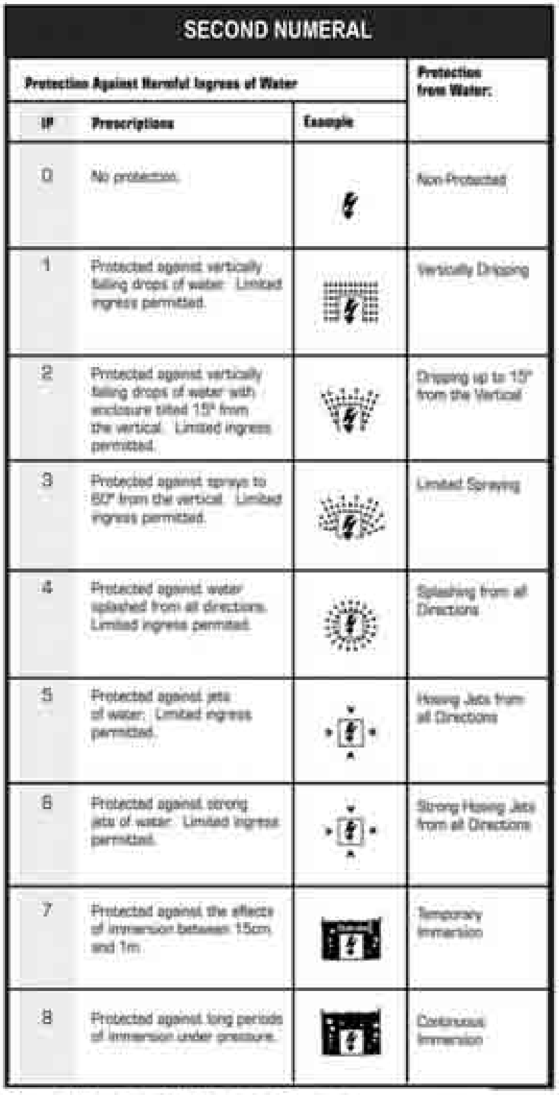
### FIRST NUMERAL

| Protection Against Ingress of Solid Objects | | | Protection of Persons Against Access to Hazardous Parts with: |
|---|---|---|---|
| **IP** | **Requirements** | **Example** | |
| 0 | No protection. | | Non-Protected |
| 1 | Full penetration of 50mm diameter sphere not allowed. Contact with hazardous parts not permitted. | | Back of Hand |
| 2 | Full penetration of 12.5mm diameter sphere not allowed. The jointed test finger shall have adequate clearance from hazardous parts. | | Finger |
| 3 | The access probe of 2.5mm diameter shall not penetrate. | | Tool |
| 4 | The access probe of 1.0mm diameter shall not penetrate. | | Wire |
| 5 | Limited ingress of dust permitted (no harmful deposit). | | Wire |
| 6 | Totally protected against ingress of dust. | | Wire |



### ADDITIONAL LETTER (OPTIONAL)

| Protection Against Ingress of Solid Objects | | | Protection of Persons Against Access to Hazardous Parts with: |
|---|---|---|---|
| **IP** | **Requirements** | **Example** | |
| A (For use with first numeral 0) | Penetration of 50mm diameter sphere up to barrier must not contact hazardous parts. | | Back of Hand |
| B (For use with first numerals 0 and 1) | Test finger penetration to a maximum of 80mm must not contact hazardous parts. | | Finger |
| C (For use with first numerals 1 and 2) | Wire of 2.5mm diameter x 10mm long must not contact hazardous parts when spherical stop face is partially entered. | | Tool |
| D (For use with first numerals 2 and 3) | Wire of 1.0mm diameter x 100mm long must not contact hazardous parts when spherical stop face is partially entered. | | Wire |

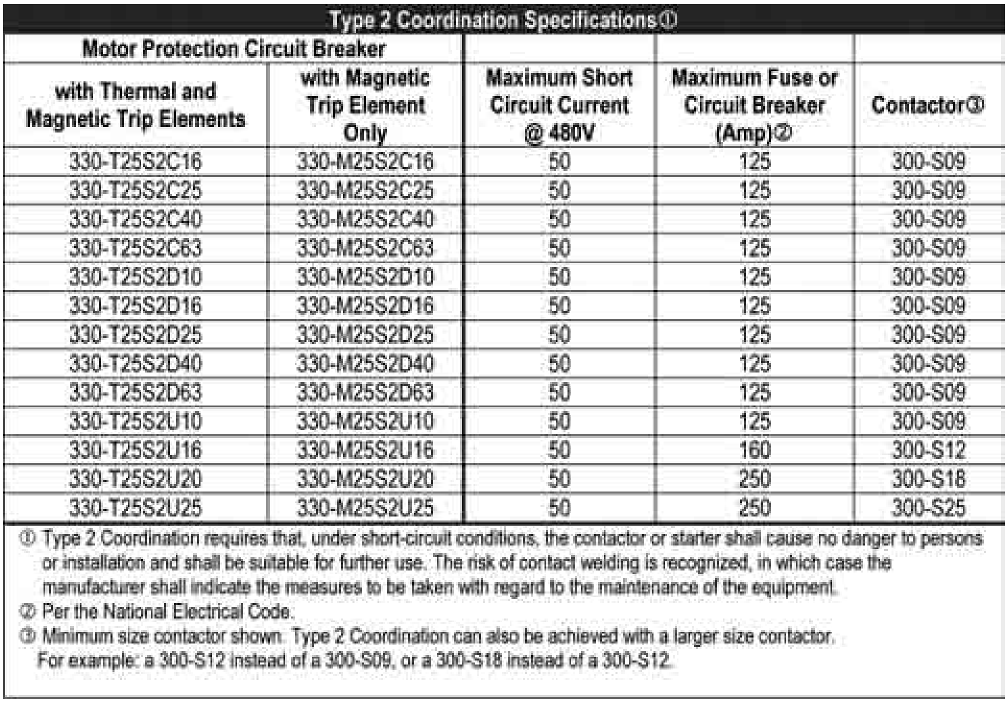


### SECOND NUMERAL

| Protection Against Harmful Ingress of Water | | | Protection from Water: |
|---|---|---|---|
| **IP** | **Prescriptions** | **Example** | |
| 0 | No protection. | | Non-Protected |
| 1 | Protected against vertically falling drops of water. Limited ingress permitted. | | Vertically Dripping |
| 2 | Protected against vertically falling drops of water with enclosure tilted 15° from the vertical. Limited ingress permitted. | | Dripping up to 15° from the Vertical |
| 3 | Protected against sprays to 60° from the vertical. Limited ingress permitted. | | Limited Spraying |
| 4 | Protected against water splashed from all directions. Limited ingress permitted. | | Splashing from all Directions |
| 5 | Protected against jets of water. Limited ingress permitted. | | Hosing Jets from all Directions |
| 6 | Protected against strong jets of water. Limited ingress permitted. | | Strong Hosing Jets from all Directions |
| 7 | Protected against the effects of immersion between 15cm and 1m. | | Temporary Immersion |
| 8 | Protected against long periods of immersion under pressure. | | Continuous Immersion |

Source: ©International Electrotechnical Commission

APPENDIX 5 – TYPE 2 COORDINATION



**Type 2 Coordination Specifications①**

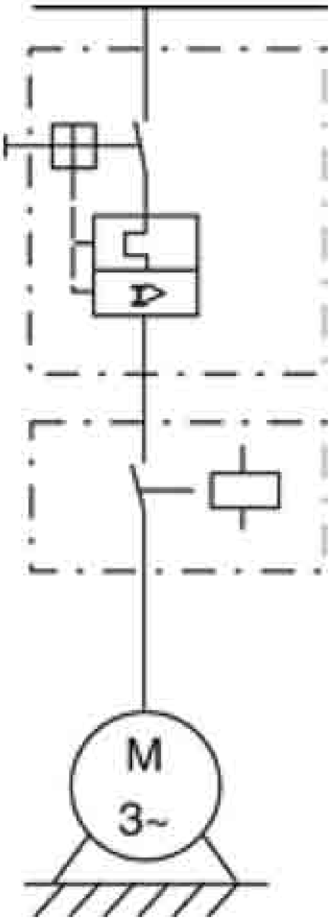
| Motor Protection Circuit Breaker | | | | |
|---|---|---|---|---|
| with Thermal and Magnetic Trip Elements | with Magnetic Trip Element Only | Maximum Short Circuit Current @ 480V | Maximum Fuse or Circuit Breaker (Amp)② | Contactor③ |
| 330-T25S2C16 | 330-M25S2C16 | 50 | 125 | 300-S09 |
| 330-T25S2C25 | 330-M25S2C25 | 50 | 125 | 300-S09 |
| 330-T25S2C40 | 330-M25S2C40 | 50 | 125 | 300-S09 |
| 330-T25S2C63 | 330-M25S2C63 | 50 | 125 | 300-S09 |
| 330-T25S2D10 | 330-M25S2D10 | 50 | 125 | 300-S09 |
| 330-T25S2D16 | 330-M25S2D16 | 50 | 125 | 300-S09 |
| 330-T25S2D25 | 330-M25S2D25 | 50 | 125 | 300-S09 |
| 330-T25S2D40 | 330-M25S2D40 | 50 | 125 | 300-S09 |
| 330-T25S2D63 | 330-M25S2D63 | 50 | 125 | 300-S09 |
| 330-T25S2U10 | 330-M25S2U10 | 50 | 125 | 300-S09 |
| 330-T25S2U16 | 330-M25S2U16 | 50 | 160 | 300-S12 |
| 330-T25S2U20 | 330-M25S2U20 | 50 | 250 | 300-S18 |
| 330-T25S2U25 | 330-M25S2U25 | 50 | 250 | 300-S25 |

① Type 2 Coordination requires that, under short-circuit conditions, the contactor or starter shall cause no danger to persons or installation and shall be suitable for further use. The risk of contact welding is recognized, in which case the manufacturer shall indicate the measures to be taken with regard to the maintenance of the equipment.

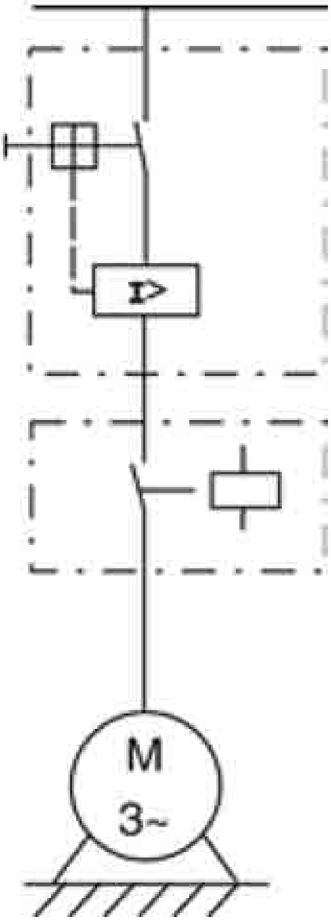
② Per the National Electrical Code.

③ Minimum size contactor shown. Type 2 Coordination can also be achieved with a larger size contactor. For example: a 300-S12 instead of a 300-S09, or a 300-S18 instead of a 300-S12.

**330-T25S & 300-S**



**330-M25S & 300-S**



# VFD FAULT DETECTIO USING MCEMAX

PdMA Corporation

As motor drives become more important in industry, the need to analyze faults associated with them increases. PdMA's MCEMAX is a great tool for analyzing faults in Variable Frequency Drives (VFDs).

Although modern technology has seen great improvement in the reliability of drives, naturally occurring events will cause faults in a drive, especially if they were originally installed in an inappropriate application. The primary focus of this article is on Pulse Width Modulated (PWM) drives without fault mode operating capabilities. Although these drives do not employ fault mode operation capability, in some cases, they will keep running even with a fault. This article will show that through the use of the MCEMAX technology, faults in these drives are detectable with a very high level of confidence.

## FAULT DETECTION

As with other predictive maintenance technologies, trending is the best method of fault detection. Trending methodology also applies to fault detection in VFDs. By trending data over a period of time, a technician is better able to detect developing problems in motors or power systems. Occasionally, faults occur that did not exhibit any trends before the occurrence, these types of failures are considered random in nature. This article covers faults that have occurred, yet, the drive continues to operate in a mode that appears normal externally.

### UPSTREAM (LINE SIDE) DIAGNOSIS

Upstream (Line Side) diagnosis of the VFD (not diagnosis of the motor) refers to testing on the incoming power to the VFD as shown in Figure 1. By testing upstream of the VFD, open diodes and open phases can be detected using the MCEMAX. Upstream diagnosis is only useful for diagnosing the VFD, do not perform overall motor diagnostics upstream of the VFD.

### OPEN DIODE

Using the MCEMAX technology, a technician is able to reliably detect an open diode fault (Figure 2) using the results from a MCEMAX Power Test.

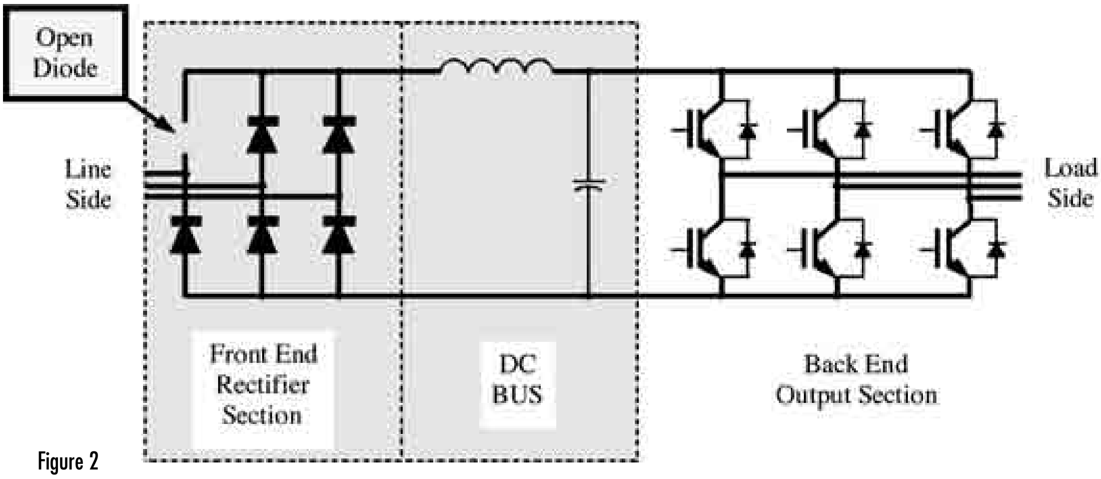


Figure 2

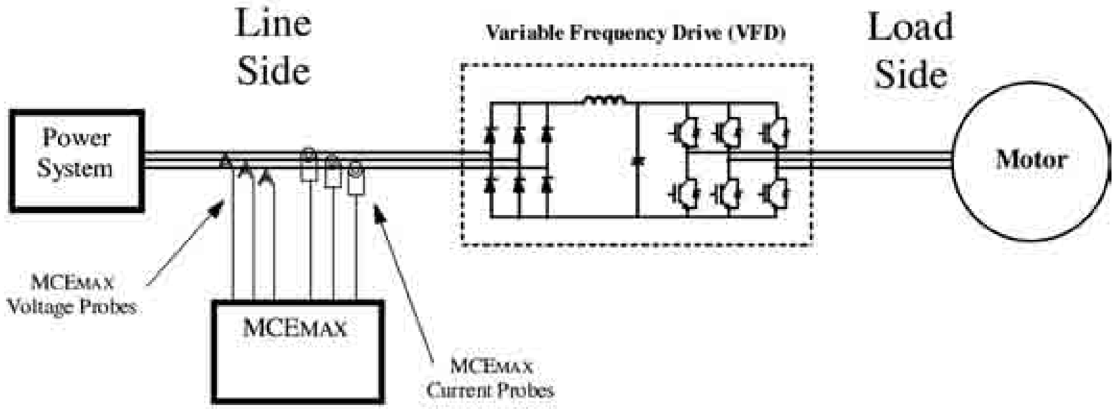


Figure 1

The phase current (Current RMS) of the phase with the open diode will decrease approximately 50% on the affected phase, and increase slightly on the other two phases (Table 1).

**Table 1**

| | Non-Faulted | Faulted |
|---|---|---|
| **Current 1 (RMS)** | 0.54 | 0.74 |
| **Current 2 (RMS)** | 0.54 | 0.29 |
| **Current 3 (RMS)** | 0.50 | 0.70 |

Percent (%) Current Imbalance will increase to approximately 50% on the affected phase (Table 2).

**Table 2**

| | Non-Faulted | Faulted |
|---|---|---|
| **% Current Imbalance** | 4.79 % | 49.32 % |

Current THD will decrease by approximately 50% on the affected phase, and increase slightly on the other two phases (Table 3).

**Table 3**

| | Non-Faulted | Faulted |
|---|---|---|
| **Current 1 (THD)** | 151.56 | 169.94 |
| **Current 2 (THD)** | 148.84 | 79.19 |
| **Current 3 (THD)** | 154.02 | 168.61 |

kW will decrease by approximately 50% on the affected phase, and increase on the remaining phases (Table 4).

**Table 4**

| | Non-Faulted | Faulted |
|---|---|---|
| **Phase 1 kW** | 0.06 | 0.09 |
| **Phase 2 kW** | 0.06 | 0.03 |
| **Phase 3 kW** | 0.06 | 0.08 |

kVAR will decrease by approximately 20% on the affected phase, and increase by approximately 40% on the remaining phases (Table 5).

**Table 5**

| | Non-Faulted | Faulted |
|---|---|---|
| **Phase 1 kVAR** | 0.11 | 0.16 |
| **Phase 2 kVAR** | 0.11 | 0.09 |
| **Phase 3 kVAR** | 0.11 | 0.15 |

kVA will decrease by approximately 20% on the affected phase, and increase by approx 40% on the remaining phases (Table 6).

**Table 6**

| | Non-Faulted | Faulted |
|---|---|---|
| **Phase 1 kVA** | 0.13 | 0.19 |
| **Phase 2 kVA** | 0.13 | 0.10 |
| **Phase 3 kVA** | 0.12 | 0.17 |

Of these methods, the best method of detection is the RMS current decrease of approximately 50% and the % Current Imbalance increase to 50%, which is detectable for all frequencies from 15 Hz to 60 Hz and loads from 0% Load (no-load) to 100% Load. The next best detection method is the current Total Harmonic Distortion (THD) decrease of approximately 50%.

After detecting a possible fault in the drive, you should try to verify the fault is in the drive, and not a measurement error. To do this, switch the test leads of the MCEMAX between two of the phases, and perform the power test again. If you receive the same results, except on a different phase, the fault is most likely in the drive.

### SHORTED DIODE

A shorted diode trips the drive on occurrence, therefore, there are no detection procedures for this type of fault.

### OPEN PHASE

An open phase occurs when a connection has come loose either at the component level or externally to the drive (Figure 3).

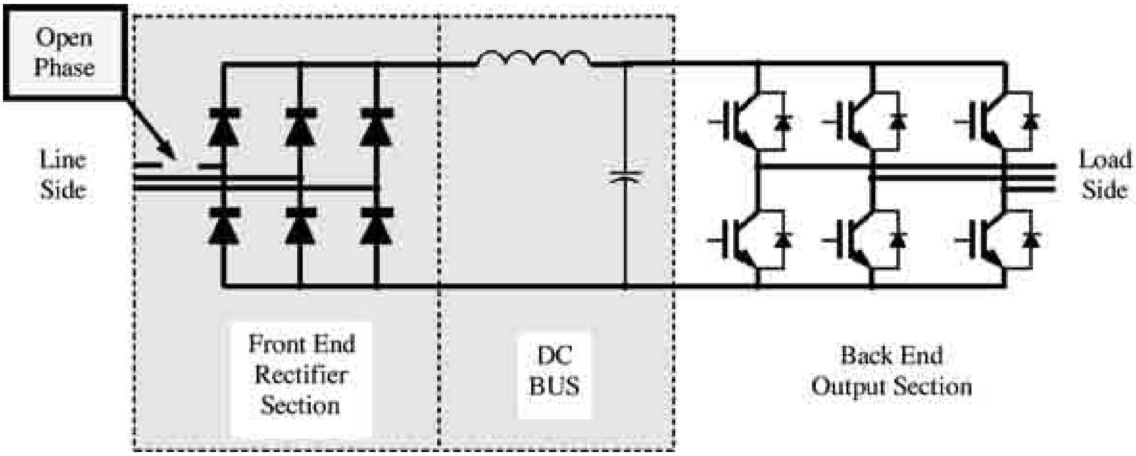


Figure 3

A technician can detect an open phase by the following:

RMS current on the faulted phase will decrease to 0.00 Amps and increase on the other two phases by approximately 90% (Table 7).

**Table 7**

| | Non-Faulted | Faulted |
|---|---|---|
| **Current 1 (RMS)** | 0.53 | 0.00 |
| **Current 2 (RMS)** | 0.52 | 0.99 |
| **Current 3 (RMS)** | 0.50 | 0.98 |

% Current Imbalance increases to approximately 100% (Table 8).

**Table 8**

| | Non-Faulted | Faulted |
|---|---|---|
| **% Current Imbalance** | 3.57 % | 99.62 % |

Current Crest Factor (CF) on the faulted phase increases to approximately 15% and there is a slight increase on the other phases (Table 9).

**Table 9**

| | Non-Faulted | Faulted |
|---|---|---|
| **Current 1 CF** | 3.51 | 15.41 |
| **Current 2 CF** | 3.37 | 4.31 |
| **Current 3 CF** | 3.66 | 4.31 |

kW decreases to 0.00 on the faulted phase and increases by approximately 50% on the other phases, but the total kW remains constant (Table 10).

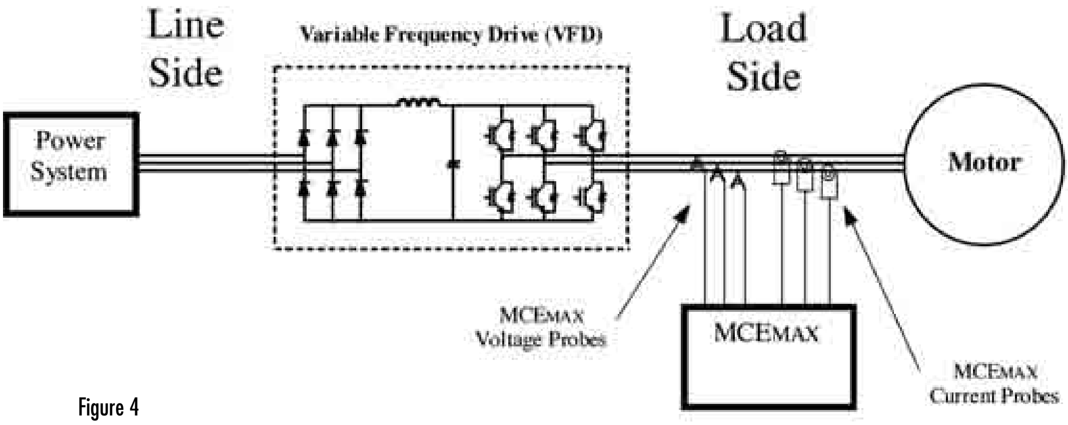


Figure 4

**Table 10**

| | Non-Faulted | Faulted |
|---|---|---|
| **Phase 1 kW** | 0.06 | 0.00 |
| **Phase 2 kW** | 0.06 | 0.09 |
| **Phase 3 kW** | 0.06 | 0.11 |
| **Total kW** | 0.19 | 0.20 |

kVAR decreases to 0.00 on the faulted phase and increases by approximately 100% on the other phases (Table 11).

**Table 11**

| | Non-Faulted | Faulted |
|---|---|---|
| **Phase 1 kVAR** | 0.11 | 0.00 |
| **Phase 2 kVAR** | 0.11 | 0.26 |
| **Phase 3 kVAR** | 0.11 | 0.25 |
| **Total kVAR** | 0.32 | 0.51 |

kVA decreases to 0.00 on the faulted phase and increases by approximately 100% on the other phases (Table 12).

**Table 12**

| | Non-Faulted | Faulted |
|---|---|---|
| **Phase 1 kVA** | 0.12 | 0.00 |
| **Phase 2 kVA** | 0.12 | 0.27 |
| **Phase 3 kVA** | 0.12 | 0.27 |
| **Total kVA** | 0.37 | 0.55 |

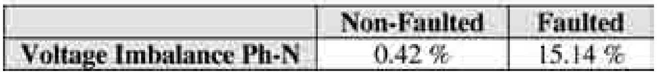
## DOWNSTREAM (LOAD SIDE) DIAGNOSIS

Downstream fault diagnosis of the VFD refers to testing on the output side of the VFD, which is between the VFD and the motor as shown in Figure 4. By testing downstream of the VFD, open diodes, and open phases can be detected using the MCEMAX. Testing downstream of the VFD is not the preferred location when performing VFD diagnostics (Line Side is the preferred location), but is the recommended test location when performing overall motor diagnostics.

### OPEN DIODE

A technician is able to detect a faulted diode in the rectifier portion of the drive by using the MCEMAX technology downstream of the drive. At 60 Hz, with the motor loaded to at least 50%, an open diode is detectable by an increase in the Phase-Neutral Voltage Imbalance to approximately 15% (Table 13).

Table 13

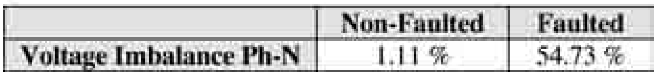


| | Non-Faulted | Faulted |
|---|---|---|
| Voltage Imbalance Ph-N | 0.42 % | 15.14 % |

### PHASE OUT

One phase that was completely out (open connection) was reliably detectable downstream of the drive when the drive was operating at 60 Hz (at any load) by an increase in the Voltage Imbalance to approximately 50%. At lower speeds, a phase out fault was not reliably detectable.

Table 14



| | Non-Faulted | Faulted |
|---|---|---|
| Voltage Imbalance Ph-N | 1.11 % | 54.73 % |

## AFTER A FAULT IS DETECTED

Once any of these faults are detected, although the drive may still be running, it is recommended that you repair or replace the drive, or contact the manufacturer of the drive for their recommendations. Failure to remedy the situation may result in excessive heat in either the drive or the motor and cause far greater losses.

## CONCLUSIONS

From our research, we found certain faults in drives can be reliably detected using the MCEMAX technology (Table 13). These faults include an open diode and an open phase. Open diodes were detectable both up and downstream of the drive. An open phase was detectable upstream of the drive at all frequencies and loads. Furthermore, an open phase was detectable downstream if the drive was running at full speed (typically 60 Hz), but it was not reliably detectable downstream if the drive frequency was below 60Hz. Future research will include a line and load side analysis of the back-end of a drive with back-end and power circuit related anomalies, and other possible detection methods using the MCEMAX technology.

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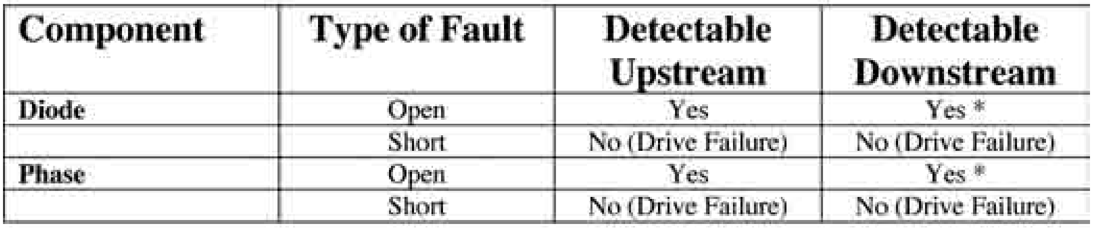
Welchko, Brian A., Lipo, Thomas A., Jahns, Thomas M., and Schulz, Steven E., "Fault Tolerant Three-Phase AC Motor Drive Topologies; A Comparison of Features, Cost, and Limitations," IEEE-International Electrical Machines and Drives Conference, June 1-4, 2003. IEEE Catalog Number 03EX679C, ISBN 0-7803-7818-0.

WJ Application Note, "MTBF Analysis for WJ Communications GaAs Devices," The Communications Edge," [http://www.wj.com/pdf/appnotes/MTBF%20Analysis%20for%20WJ%20Components_July%202002.pdf ], (July 2002).

Table 15

Fault Detection Capabilities of the MCEMAX Technology



| Component | Type of Fault | Detectable Upstream | Detectable Downstream |
|---|---|---|---|
| Diode | Open | Yes | Yes * |
| | Short | No (Drive Failure) | No (Drive Failure) |
| Phase | Open | Yes | Yes * |
| | Short | No (Drive Failure) | No (Drive Failure) |

* when the motor is run at full speed (typically 60 Hz).

# MINIMUM REQUIREMENTS, BEST PRACTICES FOR OPERATION AND MAINTENANCE OF ELECTRICAL MOTORS

Rockwell International

James Charles, David McIntosh, Maintenance Engineering Team; Mitch S. Harris, Office of Institutional Coordination; Melvin L. McCorkle, Facility Management Services

## 1.0 PURPOSE

The purpose of this article is to establish the minimum requirements and best practices for operation and maintenance of Electrical Motors at Los Alamos National Laboratory (LANL). This document addresses the requirements of LIR 230-05-01, "Operations and Maintenance Manual". (Reference 10.1)

## 2.0 SCOPE

The scope of this article includes the routine inspection, testing and maintenance of Electrical Motors at all nuclear and non-nuclear LANL facilities.

### 2.1 ELECTRICAL MOTORS

Low voltage – 600 Volts and less, Alternating Current (AC) or Direct Current (DC), excluding motors with sleeve type bearings and fractional horsepower motors with factory sealed bearings. A typical selection criterion is motors that are 3 phase, 10 to 600 horsepower, and motors with ball-type bearings.

## 3.0 ACRONYMS AND DEFINITIONS

### 3.1 ACRONYMS

AR Administrative Requirements
CFR Code of Federal Regulations
CMMS Computerized Maintenance Management System
IR Insulation Resistance Test
LIR Laboratory Implementation Requirement
NEC National Electrical Code
NEMA National Electrical Manufacturers Association
NFPA National Fire Protection Association
O&M Operations and Maintenance
PI Polarization Index Test
PP&PE Personal Property and Programmatic Equipment
PPE Personal Protective Equipment
RP&IE Real Property and Installed Equipment
SEM Systems, Engineering and Maintenance
SSC Structures, Systems, and Components
UC University of California
VOM Voltage/Ohmeter

### 3.2 DEFINITIONS

3.2.1 Continuous Duty

A requirement of motor service that demands operation at an essentially constant load for an indefinitely long time. This is the most common duty classification and accounts for approximately 90% of motor applications. (GE Motor Selection and Application Guide) (Reference 10.22)

3.2.2 Insulation Resistance Test (meggering)

A test for measuring the electrical resistance between two conductors separated by an insulating material. (McGraw-Hill Dictionary of Scientific and Technical Terms 5th Edition) (Reference 10.23)

3.2.3 Intermittent Duty

A requirement of motor service that demands operation for alternate intervals of load and no-load, load and rest, or no-load and rest. (GE Motor Selection and Application Guide) (Reference 10.22)

3.2.4 Polarization Index

The polarization index is a specialized application of the insulation resistance test. The index is the ratio of insulation resistance at two different times after voltage application, usually the insulation resistance at 10 minutes to the insulation resistance at 1 minute. (NFPA 70B 18-9.2.3) (Reference 10.4)

## 4.0 RESPONSIBILITIES

### 4.1 FACILITY MANAGER

4.1.1 Responsible for operations and maintenance of institutional, or Real Property and Installed Equipment (RP&IE), in accordance with the requirements of this document.

4.1.2 Responsible for operations and maintenance of those Personal Property and Programmatic Equipment (PP&PE) systems and equipment addressed by this document that may be assigned to the FM in accordance with the FMU-specific Facility/Tenant Agreement.

4.1.3 Responsible for system performance analysis and subsequent replacement or refurbishment of RP&IE and assigned PP&PE based on sound Life Cycle Analysis techniques and system-specific performance requirements.

### 4.2 FWO-SYSTEMS ENGINEERING AND MAINTENANCE (SEM)

4.2.1 Responsible for the technical content of this Criterion and assessing the proper implementation across the Laboratory. FWO-SEM should also provide technical assistance in support for implementation of this Criterion.

### 4.3 GROUP LEADER

4.3.1 Responsible for implementing operational and maintenance surveillance programs including the preparation and maintenance of required procedures and documentation for PP&PE under their jurisdiction that is covered by this article.

## 5.0 PRECAUTIONS AND LIMITATIONS

### 5.1 PRECAUTIONS

This section is not intended to identify all applicable precautions necessary for implementation of this Criterion (e.g., lockout/tagout, confined space entry, PPE, etc.).

It is intended only to assist the user in the identification of hazards/precautions that may not be immediately obvious.

5.1.1 Personnel must be aware of a potential for electric motors with an automatic reset protector that has the potential of automatically restarting the motor. This could endanger personnel or equipment. These auto-start features can be located on the starter itself, through programmable logic controllers or variable frequency drives.

Such applications should use a manual reset protector or an identification placard to caution personnel. Note: Lockout/Tagout procedures must always be utilized when working on or around electric motors.

5.1.2 While re-lubricating motor bearings with grease and the drain plug is removed, under no circumstances should a mechanical probe be used while the motor is in operation. Note: Lockout/Tagout procedures must always be utilized when working on or around electric motors.

5.1.3 Assure electric motor units are electrically grounded and electrical installation wiring and controls are used consistent with NEC and NFPA electrical code requirements. (NEC Article 430 and 250)

5.1.4 When approaching rotating electro-mechanical parts, such as couplings, pulleys, shafts, external fans, and unused shaft extensions, personnel should guard against accidental contact with hands, tools, or clothing. This is particularly important where the parts have surface irregularities such as keys, keyways, or setscrews.

5.1.5 Do not lift a motor and its driven load by the motor lifting hardware. Motor lifting hardware is adequate for lifting of the motor only.

### 5.2 LIMITATIONS

The intent of this Criterion is to identify the minimum generic requirements and recommendations for SSC operation and maintenance across the Laboratory. Each user is responsible for the identification and implementation of additional facilityspecific requirements and recommendations.

Nuclear facilities and moderate to high-hazard non-nuclear facilities will typically have additional facility-specific requirements beyond those presented in this Criterion which are contained in their Technical Safety Requirements, Facility Safety Plans, Configuration Management Process, and the Unreviewed Safety Question Determination (USQD) process as applicable. Nuclear facilities must implement the requirements of DOE Order 4330.4B (or 10 CFR 830.340, Maintenance Management, when issued) as the minimum programmatic requirements for a maintenance program.

Additional requirements and recommendations for SSC operation and maintenance may be necessary to fully comply with the current DOE Order or CFR identified above. (Reference 10.5)

## 6.0 REQUIREMENTS

Minimum requirements that Criterion users must follow are specified in this section.

Requested variances to these requirements must be prepared and submitted to FWOSEM in accordance with LIR 301-00-02, “Variances and Exceptions to Laboratory Operations Requirements” (Reference 10.6) for review and approval. The implementation of these requirements will ensure that the subject SSC is maintained in a condition suitable and available for its intended use. The users are responsible for analysis of operational performance and SSC replacement or refurbishment based on this analysis. The requirements contained in this section are driven by LIRs, ARs and contractually agreed to codes, orders, and standards.

### 6.1 OPERATIONS REQUIREMENTS

6.1.1 Assure machine guarding for personnel safety on motor-driven equipment remains in place while in operation.

Basis: Based upon Occupational Safety and Health Administration regulation (Reference 10.19). Compliance with this standard is required per Appendix G of the UC Contract.

### 6.2 MAINTENANCE REQUIREMENTS

6.2.1 None.

## 7.0 RECOMMENDATIONS AND GOOD PRACTICES

The information provided in this section is recommended based on acceptable industry practices and should be implemented by each user based on his/her unique application and operating history of the subject systems/equipment.

### 7.1 OPERATIONS RECOMMENDATIONS

7.1.1 Motors are designed to operate at or below any maximum surface temperature stated on the nameplate. Failure to operate the motor properly can cause this maximum motor temperature to be exceeded and cause premature failure. If applied in a hazardous area, this excessive temperature may cause ignition of hazardous materials.

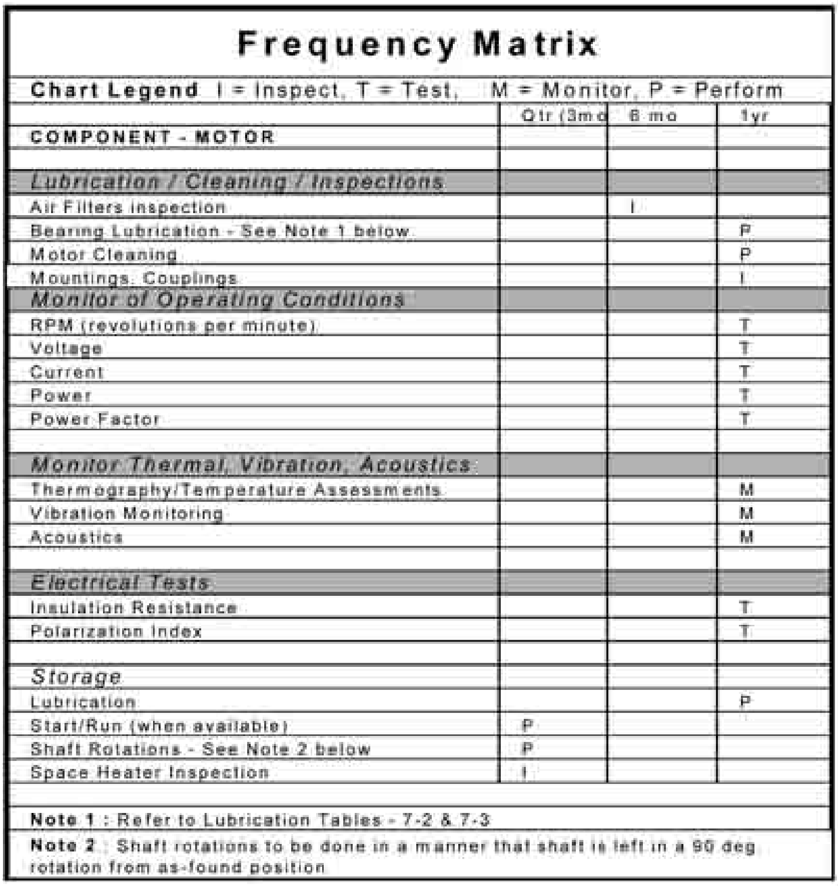
Operating motors at any of the following conditions may have the potential to cause nameplate temperatures to be exceeded:

- Motor load exceeding service factor value
- Ambient temperatures above nameplate value
- Voltages above or below nameplate value
- Unbalanced voltages
- Loss of proper ventilation
- Variable frequency operation
- Altitude above 3000 ft. Note: See 7.1.3
- Severe duty cycles – repeated starts. Note: See 7.1.2
- Motor stalls, motor reversing, or single phase operation

Basis: Recommendations provided by DOE Motor Challenge Program. (Reference 10.7)

7.1.2 Avoid repeated unsuccessful restarts of electric motors that can create overheating of motor or external starting of equipment. Generally, restarts in succession with electric motors will shorten motor life. Excessive restarts can be created both by automatic electric controls as well as manual operator actions. When additional starts are required, it is recommended that none be made until all conditions affecting operation have

Table 7.2-1 Frequency Matrix



| Frequency Matrix | | | |
|---|---|---|---|
| **Chart Legend** I = Inspect, T = Test, M = Monitor, P = Perform | | | |
| | Qtr (3mo | 6 mo | 1yr |
| **COMPONENT - MOTOR** | | | |
| | | | |
| *Lubrication / Cleaning / Inspections* | | | |
| Air Filters inspection | | I | |
| Bearing Lubrication - See Note 1 below | | | P |
| Motor Cleaning | | | P |
| Mountings, Couplings | | | I |
| *Monitor of Operating Conditions* | | | |
| RPM (revolutions per minute) | | | T |
| Voltage | | | T |
| Current | | | T |
| Power | | | T |
| Power Factor | | | T |
| | | | |
| *Monitor Thermal, Vibration, Acoustics* | | | |
| Thermography/Temperature Assessments | | | M |
| Vibration Monitoring | | | M |
| Acoustics | | | M |
| | | | |
| *Electrical Tests* | | | |
| Insulation Resistance | | | T |
| Polarization Index | | | T |
| | | | |
| *Storage* | | | |
| Lubrication | | | P |
| Start/Run (when available) | P | | |
| Shaft Rotations - See Note 2 below | P | | |
| Space Heater Inspection | I | | |
| | | | |
| **Note 1** : Refer to Lubrication Tables - 7-2 & 7-3 | | | |
| **Note 2** : Shaft rotations to be done in a manner that shaft is left in a 90 deg rotation from as-found position | | | |

been thoroughly investigated and the apparatus examined for evidence of excessive heating. It should be recognized that the number of starts should be kept to a minimum. Basis: Recommendation from National Electrical Manufactures Association - Number of Motor Starts. (Reference 10.15)

7.1.3 Los Alamos National Laboratory is located at an elevation of greater than 7000 ft.

The rating of standard motors assumes operation at sea level in a 40 deg. C ambient. For purposes of standardization it is considered that there is no difference in motor operating temperature between sea level and 3300 ft. The cooling effect of ventilating air is a function of its density. The atmospheric pressure and density at higher altitudes is reduced and the air cannot remove as much motor heat, causing the motor to run hotter. As a general guide, motor temperature rise increases 1% for every 330 ft. above 3300 ft. To keep motor heating within safe limits at altitudes above 3300 ft. the LANL Facility Engineering manual and the LANL Construction Specification Section 15170 provides provisions for de-rating motors for 7500-ft. altitude in accordance with NEMA MG1-12: 1% for every 300 ft. above 3300 ft. These specifications are requirements whenever a motor is being replaced or installed for the first time and should be utilized to provide proper cooling of motors for LANL applications.

Basis: Recommendation from National Electrical Manufacturers Association and Engineering requirements of LANL Facility Engineering Manual. (References 10.15 and 10.21)

### 7.2 MAINTENANCE RECOMMENDATIONS

Careful and regular maintenance and inspections are required to detect and clear any faults as early as possible before major damage can develop. Only general inspection intervals for trouble-free operation can be recommended because of the widely differing operating conditions. The inspection intervals must therefore be matched to the prevailing circumstances (dirt, deposits, frequent starts, loading, temperature, etc.). Special information provided by motor manufactures must also be followed. The following Maintenance Frequency Matrix is provided as a general guide.

Basis: Engineering judgement of standard industry practice and DOE Motor Challenge Program (Reference 10.7)

7.2.1 Cleaning

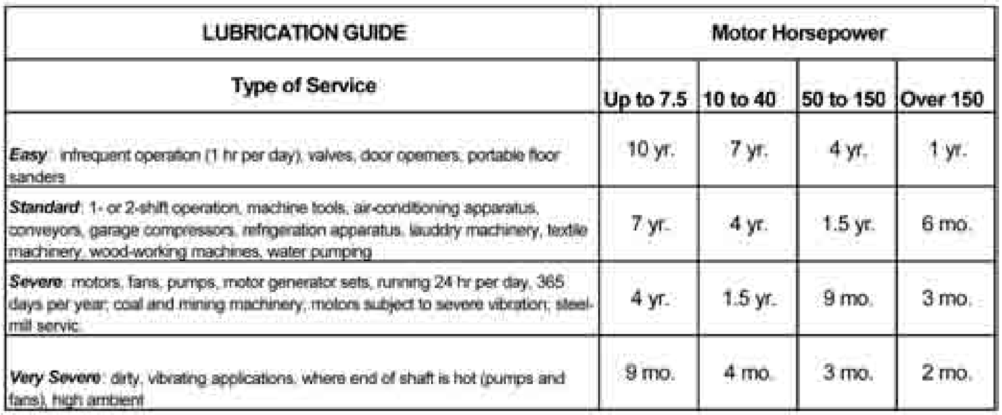
7.2.1.1 Maintain external and internal cleanliness of motors when deemed cost effective (based on size and cost of motor). Frequency will be based upon the conditions and atmosphere in which the motors operate.

Basis: Engineering judgement and Todd Litman, "Efficient Electric Motor Systems," The Fairmont Press, Inc., 1995, Lilburn, GA (Reference 10.8)

7.2.2 Lubrication

7.2.2.1 Lubricate motors based initially upon manufacturer's recommendations. Typical lubrication intervals vary from less than 3 months for large motors subject to vibration, severe bearing loads, or high temperature continuous duty to ten years for smaller motors with intermittent duty. Motors used seasonally should be lubricated before the season of use. Small or fractional horsepower motors have sealed bearings that do not require re-lubrication. All larger motors require some form of lubrication.

Refer to Appendix A for an in-depth explanation on lubrication. It is important to note that the correct quantity of lubricant is vital to the proper operation of motor bearings. Insufficient or excessive lubrication will result in failure. Reference the following lubrication frequency guide.



| LUBRICATION GUIDE | Motor Horsepower | | | |
|---|---|---|---|---|
| Type of Service | Up to 7.5 | 10 to 40 | 50 to 150 | Over 150 |
| ***Easy***: infrequent operation (1 hr per day), valves, door openers, portable floor sanders | 10 yr. | 7 yr. | 4 yr. | 1 yr. |
| ***Standard***: 1- or 2-shift operation, machine tools, air-conditioning apparatus, conveyors, garage compressors, refrigeration apparatus, lauddry machinery, textile machinery, wood-working machines, water pumping | 7 yr. | 4 yr. | 1.5 yr. | 6 mo. |
| ***Severe***: motors, fans, pumps, motor generator sets, running 24 hr per day, 365 days per year; coal and mining machinery; motors subject to severe vibration; steel-mill servic | 4 yr. | 1.5 yr. | 9 mo. | 3 mo. |
| ***Very Severe***: dirty, vibrating applications, where end of shaft is hot (pumps and fans), high ambient | 9 mo. | 4 mo. | 3 mo. | 2 mo. |

Basis: Data from vendor operation and maintenance manuals and "Incompatibility of Greases," NSK Techtalk Vol. 01, No. 02, April 1992; Technical Tip-Sheet of the NSK Corporation and "How to Get the Most From Your Electric Motors," Electric Apparatus Service Association, St. Louis, MO.; and NFPA 70B Table 19-3.7.3. (References 10.4, 10.9, 10.10)

7.2.3 Mountings and Couplings

7.2.3.1 Assure motor and load are firmly mounted to common structure or floor and motor-to-load couplings are firmly connected during maintenance performance.

Basis: Operational experience and recommendations provided by Richard L. Nailen, "Managing Motors," Barks Publications Inc., 1991, Chicago, IL. (Reference 10.11)

7.2.4 Monitoring Operating Conditions

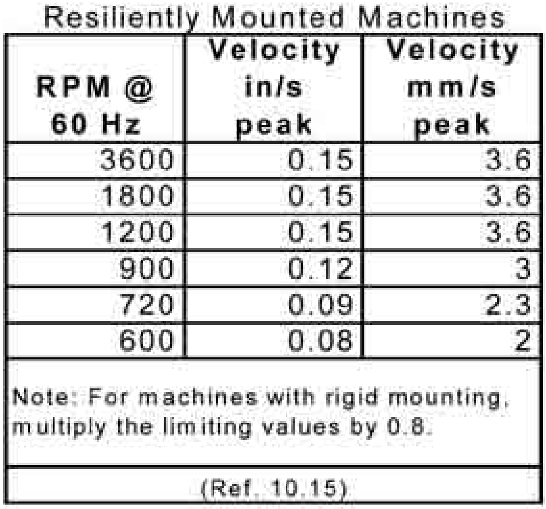
7.2.4.1 Test and monitor operating conditions at annual intervals as a minimum. Items to monitor are RPM, voltage, phase imbalance, current, power, and power factor. Maintain historical records of this monitoring. As per Section 9.1 of this document.

Basis: Standard commercial operations field experience and DOE Motor Challenge Program. (Reference 10.7)

7.2.5 Thermal, Vibration, and Acoustic Monitoring

7.2.5.1 Test electrical motors with high safety and risk levels on a routine basis for running temperature utilizing a contact thermometer at the middle of the motor housing and at the inboard and outboard bearing housings after the motor has come up to operating temperature and record (Thermography scans are acceptable as well). Test the same electrical motors for excessive vibration and acoustical noise that may alert experienced personnel to problems. Reference the following guide for guidance in motor vibration.

Table 7.2-3 Vibration Limits – Solo Run Test



Resiliently Mounted Machines

| RPM @ 60 Hz | Velocity in/s peak | Velocity mm/s peak |
|---|---|---|
| 3600 | 0.15 | 3.6 |
| 1800 | 0.15 | 3.6 |
| 1200 | 0.15 | 3.6 |
| 900 | 0.12 | 3 |
| 720 | 0.09 | 2.3 |
| 600 | 0.08 | 2 |
| Note: For machines with rigid mounting, multiply the limiting values by 0.8. | | |
| (Ref. 10.15) | | |

Basis: Operations and maintenance field experience show monitoring of critical motors closely on a routine basis has proven to be an excellent tool to prevent unsafe and/or critical conditions.

7.2.6 Electrical Tests

7.2.6.1 Regular periodic electrical tests should be performed on motors and motor circuits.

These tests are usually performed on an annual basis to detect insulation problems.

The following insulation deterioration testing techniques are predictive maintenance so that appropriate measures can be taken on a planned, and not a crash-action basis.

- Insulation resistance testing, commonly called meggering or IR, is an important predictive electrical test that is useful when the data is properly recorded and trended.
- Polarization Index (PI) is a basic IR test that goes a step further with more definitive results. The test is maintained for 10 minutes. The ten-minute reading is divided into the 1-minute reading to yield a polarization index. The PI should be above 1 and remain relatively consistent over time; a PI of 2 is very good. A pronounced drop in PI is a potential indication of a loss of insulation integrity.

Basis: Recommendations by IEEE 43-1991 and International Electrical Testing Association. (Reference 10.12, 10.13, and 10.14)

7.2.6.2 Analyze testing results of predictive/preventative maintenance records after each scheduled maintenance. Utilize NFPA 70B for acceptance criteria of data recorded.

Basis: Recommendation of DOE Motor Challenge Program and NFPA-70B 14-1.2 1998 (Reference 10.4 and 10.7).

7.2.7 Storage and Transport

7.2.7.1 Care and maintenance of spare motors is necessary to prevent premature damage leading to early failures. Lubricants can drain away or bleed, exposure to humidity can cause rust pits in bearing races and damage winding insulation, and exposures to vibration areas in a static condition will damage bearings. Several things are necessary to reduce the stress of storage. If the motors are connected, they should be started and run up to operating temperatures at a minimum quarterly basis. Motors in storage should have their shafts rotated manually on a quarterly basis to reposition the bearings and redistribute the lubricant. The shaft rotation must be done in such a way that from quarter period to quarter period, the shaft does not get rotated to its previous position but placed 90 degrees from previous as-found position. Utilizing a marking tape on the shaft and dating the time it was rotated is a good method. Some motors equipped with internal space heaters should be connected and energized to maintain a dry atmosphere within the motor.

Basis: DOE Motor Challenge Program. (Reference 10.7)

## 8.0 GUIDANCE

### 8.1 OPERATIONS GUIDANCE

8.1.1 Appropriate selection and maintenance frequency criteria for motors should be based upon two main categories in the following priority:

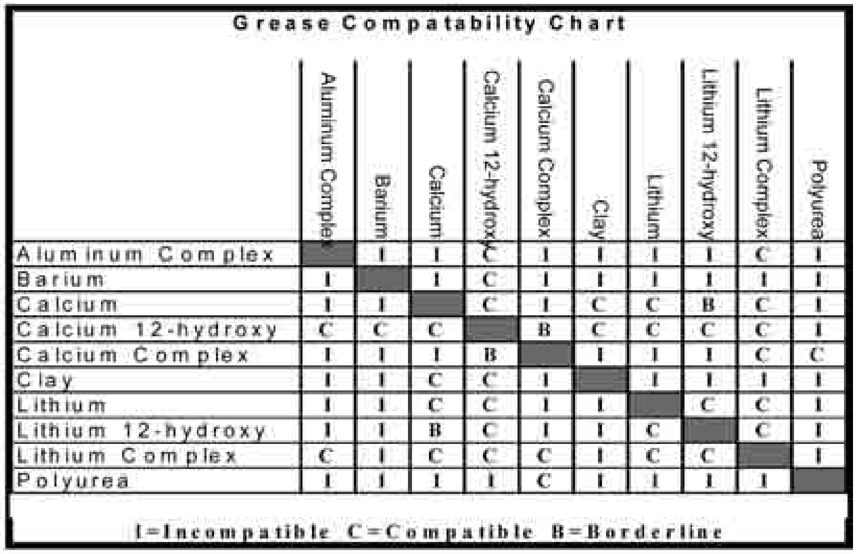
8.1.1.1 The graded approach category, that is a selective assignment of resources to the maintenance of motors based on their level of risk, mission impact, or criticality, and cost of replacement or repairs. Motors are assigned to one of four categories based on the potential impact of a worst case failure on public safety, worker safety, the environment, safeguards and security, and the programmatic function. The categories are identified as ML1, ML2, ML3, and ML4, with ML1 representing the highest level of importance and the most rigorous level of maintenance and ML4 representing the lowest level of importance and requiring less frequent maintenance activities. (Reference 10.3).

8.1.1.2 The maintain or replace approach category, that is a selective decision for each individual motor as to whether motor maintenance will be performed regularly or whether the motor will be allowed to operate until failure. The following factors to consider when making these selective decisions to maintain or replace are:

- Importance of having the motor back in service immediately
- Type and size of the motor (e.g., horsepower, efficiency rating)
- Application (speed/torque requirements), electrical operating costs and hours operated annually
- Simple payback analysis
- Cost and availability of repair service versus the cost of a new motor
- Age and repair history of the motor
- Maintenance and capital budgets

Basis: Based upon data provided by Electrical Apparatus Service Association (EASA) Chuck Yung, Technical Support Specialist, St. Louis Missouri. (Reference 10.9)

Table 8.2-1 Grease Compatibility Chart



Grease Compatability Chart

| | Aluminum Complex | Barium | Calcium | Calcium 12-hydroxy | Calcium Complex | Clay | Lithium | Lithium 12-hydroxy | Lithium Complex | Polyurea |
|---|---|---|---|---|---|---|---|---|---|---|
| Aluminum Complex | ▨ | I | I | C | I | I | I | I | C | I |
| Barium | I | ▨ | I | C | I | I | I | I | I | I |
| Calcium | I | I | ▨ | C | I | C | C | B | C | I |
| Calcium 12-hydroxy | C | C | C | ▨ | B | C | C | C | C | I |
| Calcium Complex | I | I | I | B | ▨ | I | I | I | C | C |
| Clay | I | I | C | C | I | ▨ | I | I | I | I |
| Lithium | I | I | C | C | I | I | ▨ | C | C | I |
| Lithium 12-hydroxy | I | I | B | C | I | I | C | ▨ | C | I |
| Lithium Complex | C | I | C | C | C | I | C | C | ▨ | I |
| Polyurea | I | I | I | I | C | I | I | I | I | ▨ |

I=Incompatible C=Compatible B=Borderline

## 8.2 MAINTENANCE GUIDANCE

8.2.1 Clean motors run cooler. Dirt and contaminants build up on fan-cooled motor inlet openings and fan blades reducing flow of air and increasing motor operating temperature. Surface dirt can be removed by various means. The most common means are compressed air (max. 30 psi), vacuum cleaning, and direct wipe down with rags and brushes. Internal contamination is more difficult to remove. The most effective method is to prevent internal contamination. Larger motors can have filters placed at air intake areas to reduce contamination. (Reference 10.7)

8.2.2 With further analyses and well-kept records, different types of lubricant, and/or optimized lubricant intervals improve a lubrication program. Improper greasing techniques shorten bearing and motor life. The thorough cleaning of grease relief ports, grease fittings, and grease gun nozzles prior to lubrication is necessary to allow for proper lubrication flow and for preventing introduction of contaminants. Maintaining cleanliness of lubricant and preventing introduction of contaminants into the lubricant is a very common problem. Utilizing cartridges rather than bulk lubricant can prevent some contamination problems. The free flow of grease is important to prevent damage to motor bearings. Grease guns are capable of producing high pressures that can literally drive seals and shields out of the bearing. Mixing of incompatible greases will cause bearing failures. Refer to Table 8.2-1. Adding too much grease or adding grease too frequently can force grease past bearing shields into the motor windings.

Note: It is necessary to remove old lubricants from bearings that are not compatible with introduction of new type grease. (Reference 10.10)

8.2.3 Motor and load must be rigidly bound to a common structure or floor. Failure to maintain solid mountings will lead to vibration problems that may lead to bearing failure. Coupling alignment is important to coupling and bearing life. (Reference 10.13)

8.2.4 Testing of operating speed should be performed utilizing a non-contact type tachometer for safety reasons. For belt-drive applications, it is important to measure the RPM of both the driver and the load to detect changes in slippage over time. Voltage and current checks may be performed utilizing the standard clamp-on ammeter and VOM. It is important to note phase balance because unbalance can dramatically reduce motor efficiency and life. Check both voltage and current balance. A current imbalance over 2% is cause for immediate action. Significant changes in voltage are not likely to be caused by the motor, but affect the way a motor performs. Figure 8.2-1 shows how various load performance parameters tend to change with a departure from nameplate voltage. Power and power factor may be determined utilizing power factor meter or power meter. A maintenance procedure similar to JCNNM MOI 41-50-002, "Motor Circuit Evaluation" is acceptable provided it has been reviewed and approved by FWO-SEM. (Reference 10.9 and 10.18)

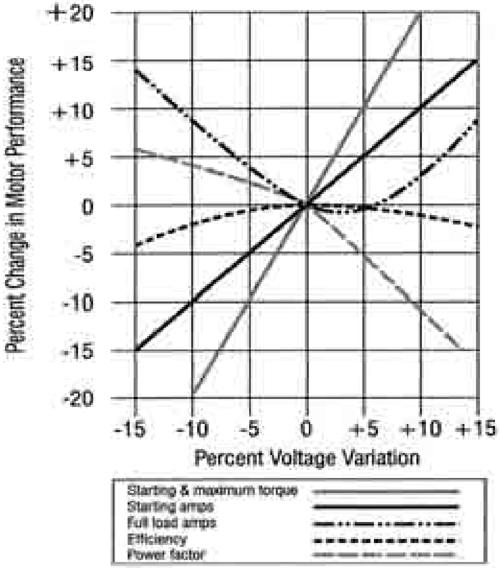


Figure 8.2-1 Effects of Voltage Variation on Induction Motor Performance Characteristics.

"Energy Management for Motor Driven Systems," US Department of Energy, Motor Challenge Program, June 1997, Rev. 1 (Reference 10.7)

8.2.5 Non Electrical Tests

8.2.5.1 Alignment

8.2.5.1.1 All rotating equipment should be properly aligned when installed. The "eyeball" and straight edge, feeler gauges, and bubble gauges do not provide the precision required.

Rim and face and reverse dial methodology, or both, should be used. For high-speed equipment and precision work, laser-alignment technology is available. Laser alignment can provide the advantages of accuracy, speed and minimum chance for operator error. If the operating temperature of equipment changes significantly, thermal expansion should be considered.

8.2.5.2 Thermal Testing

8.2.5.2.1 Thermal testing is a good problem indicator. Thermography can also be utilized for thermal testing. It is not possible to measure surface temperature of a motor only once and infer its efficiency or general health. However, over time, increases in temperature that cannot be explained by other observed factors often signal problems.

A temperature increase away from the bearing housings is usually associated with something external to the motor that can harm the motor. Check for:

- Increases in loading,
- Obstructions to cooling air flow,
- Under-voltage,
- Development of a voltage unbalance condition,
- Line harmonics, and
- Recent multiples starts, or frequent jogging.

In variable speed drive motors, low speed without a dramatic torque reduction can cause overheating. Check with the drive and motor manufacturer regarding minimum safe speed for the torque loading. Some larger motors have temperature sensors built into the stator slots. This allows for effective monitoring, trending, and alarming of motor temperature limits. A maintenance procedure similar to JCNNM MOI 41-50-0010, "Infrared Thermography" is acceptable provided it has been reviewed and approved by FWO-SEM. (Reference 10.7 and 10.16)

8.2.5.3 Vibration

8.2.5.3.1 Vibration characteristics in motors can be used to indicate mechanical and electrical problems. Characteristics from the vibration summary spectrum (frequency vs. amplitude) and time waveform (time vs. amplitude) are used to identify motor problems such as: mass unbalance, bent shaft, coupling misalignment, broken/cracked rotor bars, stator eccentricity, loose electrical connections, rotor rub, mechanical looseness and bearing deterioration. Analysis and trending of these motor defects are performed in order to forecast equipment degradation so that "as-needed planned maintenance can be performed prior to equipment failure. A maintenance procedure similar to JCNNM MOI 41-40-002, "Equipment Vibration Data Collection / Analysis" is acceptable provided it has been reviewed and approved by FWO-SEM. (Reference 10.7 and 10.17)

8.2.5.4 Acoustics

8.2.5.4.1 Acoustic monitoring can often alert experienced personnel to problems as well. The most common of these are bearing problems. Ultrasonic listening devices can sometimes detect pitting or arcing in bearings or the occurrence of arcing within windings. (Reference 10.7)

8.2.6 Establishing motor maintenance frequency is an iterative process. It is often necessary to prescribe somewhat frequent intervals at first (manufacture recommendations), then experiment with lengthening the intervals (refer to Section 7.2). Some activities can actually be harmful if performed too frequently (e.g. high voltage insulation testing and bearing greasing). If certain test results progress uniformly, you can establish a definite and often longer interval. Revise, but do not abandon the schedule. (Reference 10.7)

## 9.0 DOCUMENTATION

### 9.1 HISTORY

Data from inspection, testing, and maintenance should be recorded and controlled in equipment history files, e.g., CMMS. Computerizing the techniques proves to be the most efficient. The recorded equipment history information should be suitable to support maintenance activities, upgrade maintenance programs, optimize equipment performance, and improve equipment reliability. Utilize historical testing data to allow for trending analyses to be performed and identify needs for less or greater frequencies and weaknesses and strengths within the schedules chosen to be maintained.

### 9.2 DATA

Spreadsheets and database tools are useful for storing, manipulating, and analyzing data. Statistical software is often the best choice. DOE's Motor Challenge Program offers a special cost-free software package that is tailored specifically for motor performance and maintenance analyses (http://www.motor.doe.gov/). (Reference 10.7)

## 10.0 REFERENCES

The following references, and associated revisions, were used in the development of this article. Facility specific O&M procedures written to the requirements of this article should use the latest, LANL approved, revision of these documents.

10.1 LIR 230-05-01.0, Operation and Maintenance Manual.

10.2 DOE O 430.1A, Life Cycle Asset Management, Attachment 2, "Contractor Requirements Document," Paragraph 2, Sections A through C.

10.3 LIR 230-14-01.0, Laboratory Maintenance Management Program.

10.4 NFPA 70B-1998, Recommended Practice for Electrical Equipment Maintenance.

10.5 DOE O 4330.4B, Maintenance Management Program, Section 3.4.9.

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10.7 "Energy Management for Motor Driven Systems," US Department of Energy, Motor
Challenge Program, June 1997, Rev. 1.

10.8 "Efficient Electrical Motor Systems," Todd Litman, Fairmont Press, Inc. 1995.

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10.10 "NSK Tech Talk," Volume 1, No. 2, April 1992, Technical Tip Sheets of NSK Corporation.

10.11 "Managing Motors," Richard L. Nailen, Barks Publications, Inc. 1991.

10.12 NETA MTS-1997 International Electrical Testing Association, "Maintenance Testing Specifications for Electrical Power Distribution Equipment and Systems."

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Association, “Acceptance Testing Specifications for Electrical Power Distribution Equipment and Systems”.

10.14 IEEE Std 43-1991 The Institute of Electrical and Electronic Engineers, Inc.

“Recommended Practice for Testing Insulation Resistance of Rotating Machinery.”

10.15 NEMA MG1 – 1998 National Electrical Manufacturers Association “Motors and Generators” Sections 12.55, 12.13, and 7.8.1, Table 7-1.

10.16 JCNNM MOI 41-50-0010, “Infrared Thermography.”

10.17 JCNNM MOI 41-40-0020, “Equipment Vibration Data Collection / Analysis.”

10.18 JCNNM MOI 41-50-002, “Motor Circuit Evaluation.”

10.19 OSHA 1910.212, Occupational Safety & Health Administration “General Requirements for all Machines,” sub-part title “Machinery and Machine Guarding”.

10.20 Reliance Electric Motor Information Center, http://www.reliance.com/prodserv/motgen/b5021.htm, “Reliance Proper Motor Lubrication White Paper – B-5021.”

10.21 LANL Engineering Facility Manual, Chapter 7, Section 200, 248.5.5

10.22 GE Motor Selection and Application Guide

10.23 McGraw Hill Dictionary of Scientific and Technical Terms 5th Edition

## 11.0 APPENDIX

Appendix A: Reliance Proper Motor Lubrication White Paper – B-5021.

(See: Proper Motor Lubrication)

# PREDICTIVE MAINTENANCE TIPS FOR ELECTRIC MOTORS

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Vibration monitoring, electrical testing and visual inspections can help keep electrical motors humming along.

Electric motors are the most common source of motive power for machine trains. An effective predictive maintenance (PdM) program for them must include a combination of vibration monitoring, electrical testing and visual inspections.

**Vibration monitoring**. The vibration frequencies of the following parameters are monitored to evaluate operating condition. This information is used to establish a database.

**Bearing frequencies**. Electric motors use either sleeve or rolling-element bearings. Establish a narrowband window to monitor both normal rotational and defect frequencies associated with each bearing type.

**Imbalance**. Electric motors are susceptible to a variety of forcing functions that cause instability or imbalance. While the narrowbands are useful in identifying mechanical imbalance, other indices also should be used.

One such index is line frequency, which provides indications of instability. Modulations, or harmonics, of line frequency may indicate the motor's inability to find and hold magnetic center. In-line frequency variations also increase the amplitude of the fundamental and other harmonics of running speed. Axial movement and the resulting presence of a third harmonic of the running speed is another indication of motor instability or imbalance. The third harmonic is present whenever there is axial thrusting of a rotating element.

**Line frequency**. Many electrical problems, including those associated with the quality of the incoming power and internal to the motor, can be isolated by monitoring the line frequency. It refers to the frequency of the alternating current being supplied to the motor. In the case of 60-cycle power, monitor the fundamental or first harmonic (60 Hz), second harmonic (120 Hz), and third harmonic (180 Hz).

**Loose rotor bars**. This is a common failure mode of electric motors. Two methods can detect them.

The first uses the high-frequency vibration components caused by the oscillating rotor bars. These frequencies are well above the normal maximum frequency used to establish a broadband signature. If this is the case, a high-pass filter, such as high-frequency domain, can be used to monitor the rotor bar condition.

The second uses the slip frequency to identify loose rotor bars. The passing frequency created by this failure mode energizes modulations associated with slip. This method is preferred because these frequency components are within the normal bandwidth used for vibration analysis.

**Running speed**. The running speed of electric motors, both AC and DC, varies. For monitoring purposes, these motors are classified as variable-speed machines. Establish a narrowband window to track true running speed.

**Slip frequency**. This is the difference between synchronous speed and the motor's actual running speed. Establish a narrowband filter to monitor line frequency. The window needs enough resolution to identify clearly the frequency and the modulations, or the sidebands that represent slip frequency. Normally, these modulations are spaced at the difference between synchronous and actual speed; the number of sidebands is equal to the number of poles in the motor.

**V-belt intermediate drives**. Electric motors with these drives display the same failure modes as those described previously. However, monitor the V-belts' unique frequencies to determine if improper belt tension or misalignment is evident. In addition, electric motors with V-belt intermediate drive assemblies are susceptible to premature bearing wear.

The primary data-measurement point on the inboard bearing housing should be located in the plane opposing the induced load (sideload), with the secondary point at 90 degrees. The outboard primary data-measurement point should be in a plane opposite the inboard bearing with the secondary at 90 degrees.

**Electrical testing**. Traditional electrical testing methods must be used in conjunction with vibration analysis to prevent premature failure of electric motors. These tests should include resistance, megger, HiPot and impedance testing.

**Resistance testing**. Resistance is measured by using an ohmmeter. In reality, it does not measure resistance directly, but measures current instead. The meter is calibrated in ohms and its movement reflects the current. The amount of current supplied by the meter is very low, typically in the range of 20 to 50 microamperes. The meter functions by applying its terminal voltage to the test subject and measuring the circuit current.

For practical purposes, while resistance testing is of limited value, there are some useful tests that can be performed. A resistance test will indicate an open or closed circuit. This can tell us whether there is a break in a circuit or if there is a dead short to ground.

It's important to keep in mind that inductive and capacitive elements in the circuit distort resistance measurements. Capacitive elements appear initially as a short circuit and begin to open as they charge. They appear as open circuits when they are fully charged. Meanwhile, inductive elements appear initially as open circuits and the resistance decreases as they charge.

In both cases, the charging time is tied to the circuit's resistance, capacitance and inductance. It still requires five time constants to charge capacitors and inductors. It is also important to remember that when disconnecting the meter from the circuit, the capacitive and inductive elements are charged. Observe due caution when disconnecting test equipment.

Resistance testing coils is of limited value. It will detect an open coil or one shorted to ground, but it often will not detect shortened windings or weak insulation.

**Megger testing**. To measure very high resistances, a megohmmeter can be used. Unlike a normal ohmmeter, it measures voltage instead of measuring current to determine resistance.

This testing mode involves applying high voltage (500 to 2,500 volts, depending on the unit) to the circuit to verify there's no insulation breakdown. Generally, this is considered a non-destructive test, depending on the applied voltage and the insulation rating. A Megger is used primarily to test the integrity of insulation.

**HiPot (high potential) testing.** This potentially destructive test determines the integrity of insulation. Voltage levels used with this test are twice the rated voltage, plus 1,000 volts. Some equipment manufacturers and rebuilding facilities use the test as a quality assurance tool. It's important to note that HiPot testing does some damage to insulation every time it is performed. Because it can destroy insulation that is still serviceable, it's generally not recommended for field use.

**Impedance testing**. Impedance has two components: real (or resistive) and reactive (inductive or capacitive). This test can detect significant shorting in coils, either between turns or to ground. No other non-intrusive method is capable of detecting a coil that is shorted between turns.

**Visual and aural inspections**. A great deal can be learned about the condition of a motor just by looking at it. Here are some things to look for and how they relate to motor condition monitoring.

Dust and dirt in and around motors can cause several problems. When stuck to rotors and cooling fans, dust and dirt add weight and can cause balance problems. They also obstruct cooling airflow and provide a thermal insulation for parts that should be cooled. Dust and dirt found in and around electric motors is composed primarily of silicon (highly abrasive) and carbon (reasonable conductor of electricity). Both can puncture insulation and increase the probability of a short circuit.

Insufficient lubrication can damage bearings and cause overheating and greatly accelerate wear. Overlubricating can cause overheating, increased vibration and seal damage. Leaked lubricant is an excellent dirt magnet, resulting in both accumulation and contamination. Increased vibration shortens bearing life.

High operating temperatures also decrease bearing life. Excessive heat also breaks down insulation. Units running abnormally hot are usually not difficult to identify.

Excessive noise may indicate a mechanical or electrical problem. Usually, there is substantial vibration levels present in noisy motors.

Visual inspection of DC motors may be done while the unit is in operation. For example, some motors and generators have exposed brush/commutators/armature components.

**Brushes**. Brush condition can be evaluated visually. Replace those that appear worn, chipped or binding in their holders. In addition, look for damage to shunts, connections and clips. No brush should be worn to within 1/8 in. of any metallic part. Brush toes should be aligned parallel to commutator grooves. Any excessive arcing or sparking damages brushes, so they should be replaced.

Tamped connections without hammer springs and spring-enclosed shunts should not be worn to less than half the original length. Brush holders should be the same distance from the commutator, between 1/16 and 1/8 in.

**Commutators**. The surface of a commutator should be a uniform, glazed and dark brown in color. If the color is non-uniform or bluish, improper commutation conditions exist. Commutator slots also should be free of debris buildup. High mica or feather-edged mica may cause sparking, streaking or threading. The commutator surface should be concentric with the rotor centerline within 3 mils. Any visible radial brush movement should be corrected as soon as possible.

**Armatures**. Excessive heat and burnt odors indicate burned insulation. Charred insulation may indicate a shorted coil.

Other armature electrical defects are open and grounded coils. An open coil is indicated on a running motor by a bright spark, which appears to pass completely around the commutator. A grounded armature coil will cause a ground test lamp to flicker when the coil passes brushes. A megger test can validate the existence of these conditions.

**Final notes**. Because electric motors are critical machine-train components, an effective PdM program must include the proper techniques to monitor their operating condition. While the previous discussed techniques provide a basic program, other techniques, such as thermography, also can be used.

One final suggestion: Always remember that electric motors are designed to seek and operate at their true magnetic center. When coupled to a driven unit, either by a coupling or a flexible drive, the motor's operating dynamics are controlled directly by the driven unit's operating condition. Instability in the process or driven unit directly affects the condition of the motor.

## A

### AC (ALTERNATING CURRENT)

The commonly available electric power supplied, it is distributed in single or three-phase forms. AC current changes its direction of flow (cycles).

### AC MOTORS

A Motor (see motor definition) operating on AC current that flows in either direction (AC current). There are two general types: Induction, and Synchronous.

### ACTIVE IRON

The amount of steel (iron) in the stator and rotor of a motor. Usually the amount of active iron is increased or decreased by lengthening or shortening the rotor and stator (they

# GLOSSARY OF ELECTRIC MOTOR TERMS

Reliance Electric

## A

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The amount of steel (iron) in the stator and rotor of a motor. Usually the amount of active iron is increased or decreased by lengthening or shortening the rotor and stator (they are generally the same length).

### AIR GAP

The space between the rotating (rotor) and stationary (stator) member in an electric motor.

### AIR PRESSURE SWITCH

Used on motors with blowers to measure the difference in pressure across the filter so as to detect a clogged filter.

### AIR TEMPERATURE SWITCH

A device used in air hooded motors to detect the temperature of the exhausted air. When used in this manner, an air temperature switch will detect blockage in the cooling air system or long-term motor overload.

### ALTITUDE

The atmospheric altitude (height above sea level) at which the motor will be operating; NEMA standards call for an altitude not exceeding 3,300 ft. (1,000 meters). As the altitude increases above 3,300 ft. and the air density decreases, the air stability to cool the motor decreases - for higher altitudes higher grades of insulation or a motor derating are required. DC motors require special brushes for high altitudes.

### AMBIENT TEMPERATURE

The temperature of the surrounding cooling medium, such as gas or liquid, which comes into contact with the heated parts of the motor. The cooling medium is usually the air surrounding the motor. The standard NEMA rating for ambient temperature is not to exceed 40ƒC.

### ANTI-FRICTION BEARING

An anti-friction bearing is a bearing utilizing rolling elements between the stationary and rotating assemblies.

### ARMATURE

The portion of the magnetic structure of a DC or universal motor which rotates.

### ARMATURE CURRENT, AMPS

Rated full load armature circuit current.

### ARMATURE INDUCTANCE, MH

Armature inductance in milli-henries (saturated).

### ARMATURE REACTION

The current that flows in the armature winding of a DC motor tends to produce magnetic flux in addition to that produced by the field current. This effect, which reduces the torque capacity, is called armature reaction and can affect the commutation and the magnitude of the motor's generated voltage.

### ARMATURE RESISTANCE, OHMS

Armature resistance is measured in ohms at 25ƒ C. (cold)

### AXIAL THRUST

The force or loads that are applied to the motor shaft in a direction parallel to the axis of the shaft. (Such as from a fan or pump)

## B

### BACK END OF A MOTOR

The back end of a normal motor is the end which carries the coupling or driving pulley. (NEMA) This is sometimes called the drive end (D.E., pulley end P.E.) etc.

### BASE SPEED, RPM

The speed which a DC motor develops at rated armature and field voltage with rated load applied.

### BEARINGS

Are used to reduce friction and wear while supporting rotating elements. For a motor it must provide a relatively rigid support for the output shaft.

The bearing acts as the connection point between the rotating and stationary elements of a motor. There are various types such as roller, ball, sleeve (journal), and needle.

The ball bearing is used in virtually all types and sizes of electric motors. It exhibits low friction loss, is suited for high speed operation and is compatible in a wide range of temperatures. There are various types of ball bearings such as open, single shielded or sealed. Reliance Electric offers a unique PLS bearing system.

## BEARING LIFE

Rating life, L10 (Bl0), is the life in hours or revolutions in which 90% of the bearings selected will obtain or exceed. Median life (average life), L50(B50)

## BRAKES

An external device or accessory that brings a running motor to a standstill and/or holds a load. Can be added to a motor or incorporated.

## BRAKING TORQUE

The torque required to bring a motor down to a standstill. The term is also used to describe the torque developed by a motor during dynamic braking conditions.

## BREAK AWAY TORQUE

(See Locked rotor torque)

## BREAKDOWN TORQUE

The maximum torque a motor will develop at rated voltage without a relatively abrupt drop or loss in speed.

## BRUSH

A piece of current conducting material (usually carbon or graphite) which rides directly on the commutator of a commutated motor and conducts current from the power supply to the armature windings.

# C

## "C" FLANGE

A type of flange used with close coupled pumps, speed reducers, and similar applications where the mounting holes in the f flange are threaded to receive bolts. Normally the "C" Flange is used where a pump or similar item is to be overhung on the motor. The "C" type flange is a NEMA standard design and available with or without feet.

## CANOPY (DRIPCOVER)

A protective cover placed on the top of a motor being mounted vertically to protect it from liquids or solids that might drop onto the motor. (It acts similar to an umbrella for the motor.)

## CAPACITOR

A device which, when connected in an alternating-current circuit, causes the current to lead the voltage in time phase. The peak of the current wave is reached ahead of the peak of the voltage wave. This is the result of the successive storage and discharge of electric energy used in 1 phase motors to start or in 3 phase for power factor correction.

## CAPACITOR MOTOR

A single-phase induction motor with a main winding arranged for direct connection to the power source, and auxiliary winding connected in series with a capacitor. There are three types of capacitor motors: capacitor start, in which the capacitor phase is in the circuit only during starting, permanent-split capacitor, which has the same capacitor and capacitor phase in the circuit for both starting and running; two-value capacitor motor, in which there are different values of capacitance for starting and running.

## CAPACITOR START

The capacitor start single phase motor is basically the same as the split phase start, except that it has a capacitor in series with the starting winding. The addition of the capacitor provides a more ideal phase relation and results in greater starting torque with much less power input. As in the case of the split phase motor, this type can be reversed at rest, but not while running unless special starting and reversing switches are used. When properly equipped for reversing while running, the motor is much more suitable for this service than the split phase start as it provides greater reversing ability at less watts input.

## CENTRIFUGAL CUTOUT SWITCH

A centrifugally operated automatic mechanism used in conjunction with split phase and other types of single phase induction motors. Centrifugal cutout switches will open or disconnect the starting winding when the rotor has reached a predetermined speed, and reconnect it when the motor speed falls below it. Without such a device, the starting winding would be susceptible to rapid overheating and subsequent burnout.

## CLUTCH

A mechanical device for engaging and disengaging a motor, often used when many starts and stops are required.

## CONDUCTOR

A material, such as copper or aluminum, which offers low resistance or opposition to the flow of electric current.

## CONDUIT BOX

The metal container usually on the side of the motor where the stator (winding) leads are attached to leads going to the power supply.

## COGGING

A term used to describe non-uniform angular velocity. It refers to rotation occurring in jerks or increments rather than smooth motion. When an armature coil enters the magnetic field produced by the field coils, it tends to speed up and slow down when leaving it. This effect becomes apparent at low speeds. The fewer the number of coils, the more noticeable it can be.

## COIL (STATOR OR ARMATURE)

The electrical conductors wound into the core slot, electrically insulated from the iron core. These coils are connected into circuits or windings which carry independent current. It is these coils that carry and produce the magnetic field when the current passes through them. There are two major types: "Mush" or "random" wound, round wire found in smaller and medium motors where coils are randomly laid in slot of stator core; and formed coils of square wire individually laid in, one on top of the other, to give an evenly stacked layered appearance.

## COMMUTATOR

A cylindrical device mounted on the armature shaft and consisting of a number of wedge-shaped copper segments arranged around the shaft (insulated from it and each other. The motor brushes ride on the periphery of the commutator and electrically connect and switch the armature coils to the power source.

## COMPOUND WOUND DC MOTORS

Designed with both a series and shunt field winding, the compound motor is used where the primary load requirement is heavy starting torque, and adjustable speed is not required. (See Paralleling) Also used for parallel operation. The load must tolerate a speed variation from full-load to no-load.

Industrial machine applications include large planers, boring mills, punch presses, elevators, and small hoists.

## CONSTANT H.P.

A designation for variable or adjustable speed motors used for loads requiring the same amount of H.P. regardless of their motor speed during normal operation.

## CONSTANT TORQUE

Refers to loads whose H.P. requirements change linearly with changing speeds. Horsepower varies with the speed, i.e.- 2/1 HP at 1800/900 RPM. (Seen on some 2-speed motors). Possible applications include conveyors, some crushers, or constant-displacement pumps.

## CONSTANT SPEED

A DC motor which changes speed only slightly from a no load to a full load condition. In AC motors, these are synchronous motors.

## CORE

The iron portion of the stator and rotor; made up of cylindrical laminated electric steel. The stator and rotor cores are concentric separated by an air gap, with the rotor core being the smaller of the two and inside to the stator core.

## COUNTER ELECTROMOTIVE FORCE(CEMF)

The induced voltage in a motor armature, caused by conductors moving through or “cutting” field magnetic flux. This induced voltage opposes the armature current and tends to reduce it.

## COUPLINGS

The mechanical connector joining the motor shaft to the equipment to be driven.

## CURRENT

The time rate of flow of electrical charge and is measured in amps (amperes).

## CYCLES PER SECOND (HERTZ)

One complete reverse of flow of alternating current per rate of time. (A measure of frequency.) 60 HZ (cycles per second) A.C. power is common throughout the U.S. and 50 HZ is more common in some foreign countries.

## D

## “D” FLANGE

A special end shield with holes for through-bolts in the flange and is primarily used for mounting the motor on gear boxes or bulkheads. Standardized for frames 143T through 445T. “D” flanges are not threaded and the bolt holes extend beyond the motor frame.

## D.C. (DIRECT CURRENT)

A current that flows only in one direction in an electric circuit. It may be continuous or discontinuous and it may be constant or varying.

## DC MOTOR

A motor using either generated or rectified D.C. power (see Motor definition). A DC motor is usually used when variable speed operation is required.

## DEFINITE PURPOSE MOTOR

A definite purpose motor is any motor design, listed and offered in standard ratings with standard operating characteristics with special mechanical features for use under service conditions other than usual or for use on a particular type of application. (NEMA)

## DESIGN A, B, C, D - FOR AC MOTORS

NEMA has standard NEMA motor designs of various torque characteristics to meet the various requirements posed by different application loads. The design “B” is the most common design.

## DIMENSIONS

NEMA has standard frame sizes and dimensions designating the height of the shaft, the distance between mounting bolt holes and various other measurements. The integral AC motor NEMA sizes run from 143T- 445T, and the center of the shaft height in inches can be figured by taking the first two digits of the frame number and dividing it by 4.

The fractional horsepower motors, for which NEMA spells out dimensions, utilize 42, 48 and 56 frames whose shaft height in inches is figured by dividing the frame number by 16.

## DRIP-PROOF GUARDED

A drip-proof machine with ventilating openings guarded (with screens) as in a guarded motor.

## DRIP-PROOF MOTOR

An open motor in which the ventilating openings are so constructed that drops of liquid or solid particles falling on it, at any angle not greater than 15 degrees from the vertical, cannot enter either directly or by striking and running along a horizontal or inwardly inclined surface.

## DUAL VOLTAGE

Some motors can operate on two different voltages, depending upon how they are built and connected. The voltages are either multiples of two or the 3 of one another.

## DUAL TORQUE

Dual speed motor whose torque varies with speed (as the speed changes the horsepower remains constant).

## DUTY CYCLE

The relationship between the operating and rest times or repeatable operation at different loads. A motor which can continue to operate within the temperature limits of its insulation system, after it has reached normal operating (equilibrium) temperature is considered to have a continuous duty (CONT.) rating. One which never reaches equilibrium temperature, but is permitted to cool down between operations is operating under intermittent duty (INT.) conditions such as a crane and hoist motor which are often rated 15 or 30 min. duty.

## DYNAMOMETER

A device which loads the motor to measure output torque and speed accurately by providing a calibrated dynamic load. Helpful in testing motors for nameplate information and an effective device in measuring efficiency.

## E

## EDDY CURRENT

Localized currents induced in an iron core by alternating magnetic flux. These currents translate into losses (heat) and their minimization is an important factor in lamination design.

## EFFICIENCY

The efficiency of a motor is the ratio of mechanical output to electrical input. It represents the effectiveness with which the motor converts electrical energy into mechanical energy. NEMA has set up codes which correlate to specific nominal efficiencies. A decrease in losses (the elements keeping the motor from being 100% efficient) of 10% constitutes an upward improvement of the motor of one code on the NEMA table. Each nominal efficiency has a corresponding minimum efficiency number.

## ELECTRICAL DEGREE

A unit of measurement of time as applied to alternating current. One complete cycle = 360 electrical degrees. One cycle in a rotating electric machine is accomplished when the rotating field moves from one pole to the next pole of the same polarity. There are 360 electrical degrees in this time period. Therefore, in a two pole machine there are 360 degrees in one revolution, and the electrical and mechanical degrees are equal. In a machine with more than two poles, the number of electrical degrees per revolution is obtained by multiplying the number of pairs of poles by 360.

## ELECTRICAL TIME CONSTANT (FOR DC MOTORS)

The ratio of electrical inductance to armature resistance. Electrical time constant in seconds defined as Electrical where La is the armature circuit inductance in henries and la is the rated full load armature current.

## ELECTRICAL UNBALANCE

In a 3-phase supply, where the voltages of the three different phases are not exactly the same. Measured in % of unbalance.

## ELECTROMOTIVE FORCE (EMF)

A synonym for voltage, usually restricted to generated voltage.

## ENCAPSULATED WINDING

A motor which has its winding structure completely coated with an insulating resin (such as epoxy). This construction type is designed for exposure to more severe atmospheric conditions than the normal varnished winding.

## ENCLOSURES

The housing, frame, of the motor of which there are two broad classifications; open and totally closed. There are specific types of each:

### MOTOR ENCLOSURES

Reliance Electric offers the industry's widest selection of motor/generator enclosures to meet specific operating needs.

ODG - Open Drip-Proof, Guarded
ODG-FV - Open Drip-Proof, Force Ventilated
ODG-SV - Open Drip-Proof, Separately Ventilated
ODP - Open Drip-Proof
HP - Vertical P-Base, Normal Thrust
LP - Vertical P-base, Medium Thrust, Extended Thrust
Prot. - Protected
TEAO - Totally-Enclosed, Air-Over
TEBC - Totally-Enclosed, Blower-Cooled
TECACA - Totally-Enclosed, Closed Circuit,, Air to Air
TEDC-A/A - Totally-Enclosed, Dual Cooled, Air to Air
TEDC-A/W - Totally-Enclosed, Dual Cooled, Air to Water
TEFC - Totally-Enclosed, Fan-Cooled
TENV - Totally-Enclosed Non-Ventilated
TETC - Totally-Enclosed, Tube Cooled
TEWAC - Totally-Enclosed, Water/Air Cooled
TEXP - Totally-Enclosed, Explosion-Proof
IP-22 - Open Drip-Proof
IP-44 - Totally-Enclosed
IP-54 - Splash Proof
IP-55 - Washdown
WPI - Weather Protected, Type I
WPII - Weather Protected Type II
XE - Premium Efficient
XL - Extra Life
XP - Explosion-Proof
XT - Extra Tough

## ENDSHIELD

The part of the motor housing which supports the bearing and acts as a protective guard to the electrical and rotating parts inside the motor. This part is frequently called the "end bracket" or "end bell".

## EXPLOSION-PROOF ENCLOSURE

A totally enclosed enclosure which is constructed to withstand an explosion of a specified gas, vapor or dust which may occur within it. Should such an explosion occur, the enclosure will prevent the ignition or explosion of the gas or vapor which may surround the motor enclosure. These motors are listed with Underwriter's Laboratories.

## EXPLOSION-PROOF-HAZARDOUS LOCATIONS

DIVISION I - Location in which ignitable concentrations of flammable or combustible material exist and come in contact with the motor.

DIVISION 11 - Locations in which ignitable concentrations of flammable or combustible material exist but are contained within closed systems or containers and normally would not come in contact with the motor.

EXPLOSION-PROOF-U.L. CLASSIFICATIONS CLASS I -Those in which flammable gasses or vapors are or may be present in the air in quantities sufficient to produce explosive or ignitable mixtures.

Group C - Atmospheres containing ethyl or ether vapors.

Group D - Atmospheres containing gasoline, hexane, benzene, butane, propane, alcohols, acetone, benzol, lacquer solvent vapors, natural gas, etc.

Class 11 - Those which are hazardous because of the presence of combustible dust.

Group E - Atmospheres containing metal dust, including aluminum, magnesium, or their commercial alloys.

Group F - Atmospheres containing carbon black, charcoal, coal or coke dust.

Group G - Atmospheres containing flour, starch, grain or combustible plastics or chemical dusts.

## EXTERNALLY VENTILATED

A motor using an external cooling system. This is required in applications where the motor's own fan will not provide sufficient cooling; this is true for certain duty cycle applications, slow speed motors, also in environments with extreme dirt. Often a duct with an external blower is used to bring clean air into the motor's air-intake.

## F

## FIELD

A term commonly used to describe the stationary (Stator) member of a DC Motor. The field provides the magnetic field with which the mechanically rotating (Armature or Rotor) member interacts.

## FIELD WEAKENING

The introduction of resistance in series with the shunt wound field of a DC motor to reduce the voltage and current which weakens the strength of the magnetic field and thereby increases the motor speed.

## FLANGE

Mounting endshield with special rabbets and bolt holes for mounting such equipment as pumps and gear boxes to the motor or for overhanging the motor on the driven machine.

## FLUX

The magnetic field which is established around an energized conductor or permanent magnet. The field is represented by flux lines creating a flux pattern between opposite poles. The density of the flux lines is a measure of the strength of the magnetic field.

## FORM FACTOR

A figure of merit which indicates how much rectified current departs from pure (non-pulsating) DC. A large departure from unity form factor (pure DC, expressed as 1.0) increases the heating effect of the motor and reduces brush life. Mathematically, form factor is the ratio of the root-mean square (rms) value of the current to the average (av) current or Irms/lav.

## FORM WOUND

A type of coil in which each winding is individually formed and placed into the stator slot. A cross sectional view of the winding would be rectangular. Usually form winding is used on high voltage, 2300 volts and above, and large motors (449T and above). Form winding allows for better insulation on high voltage than does random (mush) winding.

## FRACTIONAL-HORSEPOWER MOTOR

A motor usually built in a frame smaller than that having a continuous rating of one horsepower, open construction, at 1700 -1800 rpm. Within NEMA frame sizes FHP encompasses the 42, 48 and 56 frames. (In some cases the motor rating does exceed 1 HP, but the frame size categorizes the motor as a fractional.) The height in inches from the center of the shaft to the bottom of the base can be calculated by dividing the frame size by 16.

## FRAME

The supporting structure for the stator parts of an AC motor; in a DC motor the frame usually forms a part of the magnetic coil. The frame also determines mounting dimensions (see frame size).

## FRAME SIZE

Refers to a set of physical dimensions of motors as established by NEMA. These dimensions include critical mounting dimensions. 48 and 56 frame motors are considered fractional horsepower sizes even though they can exceed 1 horsepower, 143T to 449T are considered integral horsepower AC motors and 5000 series and above are called large motors. (For definition of letters following frame number, see Suffixes.)

## FREQUENCY

The rate at which alternating current makes a complete cycle of reversals. It is expressed in cycles per second. In the U.S. 60 cycles (Hz) is the standard while in other countries 50 Hz (cycles) is more common. The frequency of the AC will affect the speed of a motor (see Speed).

## FRONT END OF A MOTOR

The front end of a normal motor is the end opposite the coupling or driving pulley. (NEMA) This is sometimes called the opposite pulley end (O.P.E.) or commutator end (C.E.).

## FULL-LOAD CURRENT

The current flowing through the line when the motor is operating at full-load torque and full-load speed with rated frequency and voltage applied to the motor terminals.

## FULL-LOAD TORQUE

That torque of a motor necessary to produce its rated horsepower at full-load speed, sometimes referred to as running torque.

## G

## GEARHEAD

The portion of a gearmotor which contains the actual gearing which converts the basic motor speed to the rated output speed.

## GEARMOTOR

A gearhead and motor combination to reduce the speed of the motor to obtain the desired RPMs.

## GENERAL PURPOSE MOTOR

A general-purpose motor is any motor having a “B” design, listed and offered in standard ratings with standard operating characteristics and mechanical construction for use under usual service conditions without restriction to a particular application or type of application. (NEMA)

## GROUNDED MOTOR

A motor with an electrical connection between the motor frame and ground.

## GUARDED MOTOR

An open motor in which all openings giving direct access to live or rotating parts (except smooth shafts) are limited in size by the design of the structural parts or by screens, grills, expanded metal, etc., to prevent accidental contact with such parts. Such openings shall not permit the passage of a cylindrical rod 1/2 inch in diameter.

## H

## HEAT EXCHANGER

A device which will transfer the heat from inside the motor to another medium, through a radiator type heat exchanger.

## HERTZ (HZ)

One cycle per second (as in 60 Hz. which is 60 cycles per second).

## HORSEPOWER

The measure of rate of work. One horsepower is equivalent to lifting 33,000 pounds to a height of one foot in one minute. The horsepower of a motor is expressed as a function of torque and rpm. For motors the following approximate formula may be used:

where HP = horsepower, T = torque (in. lb.ft.), and RPM = revolutions per minute.

## HYSTERESIS LOSS

The resistance offered by materials to becoming magnetized (magnetic orientation of molecular structure) results in energy being expended and corresponding loss. Hysteresis loss in a magnetic circuit is the energy expended to magnetize and demagnetize the core.

## I

## IDENTIFICATION

In most instances, the following information will help identify a motor:

1. Frame designation (actual frame size in which the motor is built).
2. Horsepower, speed, design and enclosure.
3. Voltage, frequency and number of phases of power supply.
4. Class of insulation and time rating.
5. Application

## INDUCTANCE

The characteristic of an electric circuit by which varying current in it produces a varying magnetic field which causes voltages in the same circuit or in a nearby circuit.

## INDUCTION MOTOR

An induction motor is an alternating current motor in which the primary winding on one member (usually the stator) is connected to the power source and a secondary winding or a squirrel-cage secondary winding on the other member (usually the rotor) carries the induced current. There is no physical electrical connection to the secondary winding, its current is induced.

## INERTIAL LOAD

A load (flywheel, fan, etc.) which tends to cause the motor shaft to continue to rotate after the power has been removed (stored kinetic energy). If this continued rotation cannot be tolerated, some mechanical or electrical braking means must normally be applied . This application may require a special motor due to the energy required to accelerate the inertia. Inertia is measured in either lb.ft.2 or OZ.jn.2

Inertia reflected to the shaft of the motor = (Load RPM) 2/Motor RPM

## INSULATOR

A material which tends to resist the flow of electric current (paper, glass, etc.) In a motor the insulation serves two basic functions:

1. Separates the various electrical components from one another.
2. It protects itself and the electrical components from attack of contaminants and other destructive forces.

## INSULATION SYSTEMS

Five specialized elements are used, which together constitute the motor’s INSULATION SYSTEM. The following are typical in an AC motor:

1. TURN-TO-TURN INSULATION between separate wires in each coil. (Usually enamel on random wound coils of smaller motors - tape on “form wound” coils of larger motors.)
2. PHASE-TO-PHASE INSULATION between adjacent coils in different phase groups. (A separate sheet material on smaller motors - not required on form wound coils because the tape also performs this function.)
3. PHASE-TO-GROUND INSULATION between windings as a whole and the “ground” or metal part of the motor. (A sheet material, such as the liner used in stator slots, provides both di-electric and mechanical protection.)
4. SLOT WEDGE to hold conductors firmly in the slot.
5. IMPREGNATION to bind all the other components together and fill in the air spaces. (A total impregnation, applied in a fluid form and hardened, provides protection against contaminants.)

## INSULATION CLASS

Since there are various ambient temperature conditions a motor might see and different temperature ranges within which motors run and insulation is sensitive to temperature; motor insulation is classified by the temperature ranges at which it can operate for a sustained period of time.

## INTERMITTENT DUTY

A requirement of service that demands operation for alternate intervals of (1 ) load and no load; or (2) load and rest; or (3) load, no load and rest; such alternate intervals being definitely specified.

## INTERPOLES

An auxiliary set of field poles carrying armature current to reduce the field flux caused by armature reaction in a DC motor.

## INVERTER

An electronic device that converts fixed frequency and fixed voltages to variable frequency and voltage. Enables the user to electrically vary the speed of an AC motor.

## I2R

Losses due to current flowing in a conductor caused by resistance (equals the current squared times the resistance).

## J

## J SECONDS (DC MOTORS)

J is the per unit moment of inertia. It is defined as the time in seconds to accelerate the motor armature to rated base speed using rated full load torque.

$$J = \frac{\text{WR2x Base Rpm(seconds)}}{\text{308 x Rated Torque}}$$

## JACKSCREW

A device used for leveling the positioning of a motor. These devices are adjustable screws fitting on the base or motor frame. Also a device for removing endshields from a motor assembly.

## K

## KILOWATT

Since the watt is a relatively small unit of power, the kilowatt (kw), 1,000 watts, is used where larger units of power measurements are desirable.

## L

## LAMINATIONS

The steel portion of the rotor and stator cores made up of a series of thin laminations (sheets) which are stacked and fastened together by cleats, rivets or welds. Laminations are used instead of a solid piece in order to reduce eddy-current losses.

## LARGE MOTORS

Usually refers to AC motors in 5,000 series frames and above and to 500 series frames and larger in DC.

## LOAD

The burden imposed on a motor by the driven machine. It is often stated as the torque required to overcome the resistance of the machine it drives. Sometimes “load” is synonymous with “required power”.

## LOCKED ROTOR CURRENT

Steady state current taken from the line with the rotor at standstill (at rated voltage and frequency). This is the current seen when starting the motor and load.

## LOCKED ROTOR TORQUE

The minimum torque that a motor will develop at rest for all angular positions of the rotor (with rated voltage applied at rated frequency).

## LOSSES

A motor converts electrical energy into a mechanical energy and in so doing, encounters losses. These losses are all the energy that is put into a motor and not transformed to usable power but are converted into heat causing the temperature of the windings and other motor parts to rise.

## LUBRICATION

In order to reduce wear and avoid overheating certain motor components require lubricating (application of an oil or grease). The bearings are the major motor component requiring lubrication (as per manufacturer’s instructions). Excess greasing can however damage the windings and internal switches, etc. (See PLS)

## M

## MAGNETIC POLARITY

It is a fundamental principle of a winding that adjacent poles must be wound to give opposite magnetic polarity. This does not mean that the coils actually have to be wound in this direction before being placed into the stator. It does mean that the winding must be connected so that, if the current proceeds through one pole in a clockwise direction, it must proceed through the next pole in a counterclockwise direction. This principle is used to determine the correctness of connection diagrams.

## MEDIUM MOTORS

Motors in NEMA 143T to 449T frames.

## MEGGAR TEST

A measure of an insulation system’s resistance. This is usually measured in megohms and tested by passing a high voltage at low current through the motor windings and measuring the resistance of the various insulation systems.

## MOTOR

A device that takes electrical energy and converts it into mechanical energy to turn a shaft.

## MULTI-SPEED MOTORS

A motor wound in such a way that varying connections at the starter can change the speed to a predetermined speed. The most common multi-speed motor is a two speed although three-

and four-speeds are sometimes available. Multi-speed motors can be wound with two sets of windings or one winding. They are also available either constant torque, variable torque or constant horsepower.

## N

### NAMEPLATE

The plate on the outside of the motor describing the motor, HP, voltage, RPM's, efficiency, design, enclosure, etc.

### NAVY SERVICE "A"

Motors designed to meet requirements of MIL M-17059 or MlL M-17060 for high shock and service and are essential to the combat effectiveness of a ship. These motors are usually made of nodular iron.

### N.E.C. TEMPERATURE CODE ('T' CODE)

An index for describing maximum allowable "skin" (surface) temperature of a motor under any normal or abnormal operating conditions. The "T" codes are applicable to U.L. listed explosion-proof motors. The skin temperature shall not exceed the minimum ignition temperature of the substances to be found in the hazardous location. The "T" code designations apply to motors and other types of electrical equipment subject to hazardous location classification.

### NEMA

The National Electrical Manufacturers Association (http://www.nema.org) is a non-profit organization organized and supported by manufacturers of electric equipment and supplies. NEMA has set standards on:

H.P. ratings
speeds
frame sizes and dimensions
standard voltages and frequencies with allowable variations
service factors
torques
starting current & KVA
enclosures

### NEMA I

See Weather protected machine, Type I

### NEMA 11

See Weather protected machine, Type 11

### NODULAR IRON (DUCTILE IRON)

Special cast iron with a crystalline formation which makes it capable of handling high shock.

## O

### OIL MIST LUBRICATION-DRY SUMP

A method for lubricating anti-friction bearings which utilizes oil dispersed on an air stream. The mist is exhausted from the bearing housing so as not to permit oil to accumulate.

### OIL MIST LUBRICATION-WET SUMP

Similar to Oil Mist Lubrication - Dry Sump, except that a pool of oil is developed in the bearing chamber. This oil pool will continue to supply oil to the bearing in the event that the oil mist is interrupted and is fed from a source outside the bearing housing such as a constant level oiler.

### OPEN BEARING

A ball bearing that does not have a shield, seal or guard on either of the two sides of the bearing casing.

### OPEN EXTERNALLY-VENTILATED MACHINE

A machine which is ventilated with external air by means of a separate motor-driven blower mounted on machine enclosure.

### OPEN PIPE-VENTILATED MACHINE

An open machine except that openings for admission of ventilating air are so arranged that inlet ducts or pipes can be connected to them. Air may be circulated by means integral with machine or by means external to and not a part of the machine. In the latter case, this machine is sometimes known as separately- or force-ventilated machine.

### OPEN (PROTECTED) MOTOR

A motor having ventilating openings which permit passage of external cooling air over and around the windings. The term "open machine", when applied to large apparatus without qualification, designates a machine having no restriction to ventilation other than that necessitated by mechanical construction.

## P

### "P" BASE

A special mounting similar to "D" flange except with a machine fit tenon recessed instead of protruding. Usually found on pumps.

### PLS

An exclusive Reliance Electric bearing and lubricating system which permits complete lubrication of the bearing whether the motor is mounted vertically or horizontally. This system also helps prevent over lubrication which would shorten motor life. An additional benefit to PLS lubrication is cooler running bearings.

### PARALLELING

When two or more DC motors are required to operate in parallel - that is, to drive a common load while sharing the load equally among all motors - they should have speed-torque characteristics which are identical. The greater the speed droop with load, the easier it becomes to parallel motors successfully. It follows that series motors will operate in parallel easier than any other type. Compound motors, which also have drooping speed characteristics (high regulation), will generally parallel without special circuits or equalization. It may be difficult to operate shunt or stabilized-shunt motors in parallel because of their nearly constant speed characteristics. Modifications to the motor control must sometimes be made before these motors will parallel within satisfactory limits.

### PART WINDING START MOTOR

Is arranged for starting by first energizing part of the primary winding and subsequently energizing the remainder of this winding in one or more steps. The purpose is to reduce the initial value of the starting current drawn or the starting torque developed by the motor. A standard part winding start induction motor is arranged so that one-half of its primary winding can be energized initially and subsequently the remaining half can be energized, both halves then carrying the same current.

## PERMANENT MAGNET SYNCHRONOUS (PMR) (HYSTERESIS SYNCHRONOUS)

A motor with magnets embedded into the rotor assembly, which enable the rotor to align itself with the rotating magnetic field of the stator. These motors have zero slip (constant speed with load) and provide higher torque, efficiency and draw less current than comparable reluctance synchronous motors.

## PHASE

Indicates the space relationships of windings and changing values of the recurring cycles of A.C. voltages and currents. Due to the positioning (or the phase relationship) of the windings, the various voltages and currents will not be similar in all aspects at any given instant. Each winding will lead or lag another, in position. Each voltage will lead or lag another voltage, in time. Each current will lead or lag another current, in time. The most common power supplies are either single (10) or three phase (with 120 electrical degrees between the 3 phases).

## PLUG REVERSAL

Reconnecting a motor's winding in reverse to apply a reverse braking torque to its normal direction of rotation while running. Although it is an effective dynamic braking means in many applications, plugging produces more heat than other methods and should be used with caution .

## POLARIZATION TEST

A ratio of a one-minute meggar test (see Meggar Test) to ten-minute meggar test. Used to detect contaminants in winding insulation done typically on high voltage, V.P.I. motors which are tested by water immersion.

## POLES

In an AC motor, refers to the number of magnetic poles in the stator winding. The number of poles is a determinant of the motor's speed. (See Synchronous Speed)

In a DC motor, refers to the number of magnetic poles in the motor. Creates the magnetic field in which the armature operates. (Speed is not determined by the number of poles).

## POLYPHASE MOTOR

Two- or three-phase induction motors have their windings, one for each phase, evenly divided by the same number of electrical degrees. Reversal of the two-phase motor is accomplished by reversing the current through either winding. Reversal of a three-phase motor is accomplished by interchanging any two of its connections to the line. Polyphase motors are used where a polyphase (three-phase) power supply is available and is limited primarily to industrial applications.

Starting and reversing torque characteristics of polyphase motors are exceptionally good. This is due to the fact that the different windings are identical and, unlike the capacitor motor, the currents are balanced. They have an ideal phase relation which results in a true rotating field over the full range of operation from locked rotor to full speed.

## POWER CODE

Identifies the type of power supply providing power to a DC motor. Frequency, voltage, and type of rectifier configuration.

## POWER FACTOR

A measurement of the time phase difference between the voltage and current in an AC circuit. It is represented by the cosine of the angle of this phase difference. For an angle of 0 degrees, the power factor is 100% and the volt/amperes of the circuit are equal to the watts. (This is the ideal and an unrealistic situation.) Power factor is the ratio of Real Power-KW to total KVA or the ratio of actual power (watts) to apparent power (volt-amperes).

## PRIMARY WINDING

That winding of a motor, transformer or other electrical device which is connected to the power source.

## PROTECTIVE RELAY

A relay, the principal function of which is to protect service from interruption, or to prevent or limit damage to apparatus.

## PULL-IN TORQUE

The maximum constant torque which a synchronous motor will accelerate into synchronism at rated voltage and frequency.

## PULL-UP TORQUE

The minimum torque developed by an AC motor during the period of acceleration from zero to the speed at which breakdown occurs. For motors which do not have a definite breakdown torque, the pull-up torque is the minimum torque developed during the process of getting up to the rated speed.

R - R (r bar) is the per unit armature circuit resistance using counter emf as a base.

$$R = \frac{\text{Hot IR voltage drop}}{\text{Terminal volts - (Hot IR voltage drop)}}$$

where

Hot IR voltage drop = (Rated lax Hot Arm. Cir. Resistance) + 2.0 (Brush drop) volts.

## R

## R.P.M.: (REVOLUTIONS PER MINUTE)

The number of times per minute the shaft of the motor (machine) rotates. This is a function of design and the power supply.

## RANDOM WOUND

The standard type of stator winding used in motors under 1,000 volts. The coils are random wound with round wire as opposed to flat form wound coils.

## RTD (RESISTANCE THERMAL DETECTORS)

### WINDING RTD

A resistance device used to measure temperature change in the motor windings to detect a possible overheating condition. These detectors would be embedded into the winding slot and their resistance varies with the temperature.

### BEARING RTD

A probe used to measure bearing temperature to detect an overheating condition. The RTD's resistance varies with the temperature of the bearings.

## REACTANCE (INDUCTIVE)

The characteristic of a coil, when connected to alternating current, which causes the current to lag the voltage in time phase. The current wave reaches its peak later than the voltage wave reaches its peak.

## RELAY

A device that is operative by a variation in the conditions of one electric circuit to affect the operation of other devices in the same or another electric circuit.

## RELUCTANCE

The characteristic of a magnetic material which resists the flow of magnetic lines of force through it.

## RELUCTANCE SYNCHRONOUS MOTOR

A synchronous motor with a special rotor design which directly lines the rotor up with the rotating magnetic field of the stator, allowing for no slip under load. The reluctance motors have lower efficiencies, power factors and torques than their permanent magnet counterparts.

## RESISTANCE

The degree of obstacle presented by a material to the flow of electric current is known as resistance and is measured in ohms.

## RESILIENT MOUNTING

A suspension system or cushioned mounting designed to reduce the transmission of normal motor noise and vibration to the mounting surface. This type of mounting is typically used in fractional motors for fans and blowers.

## REVERSING

Unless otherwise specified, a general-purpose DC motor is reversible. A DC motor can be reversed by changing the polarity of the field or the armature, but not both. When rapid reversing is necessary, the armature circuit is reversed. In some cases, it is frequently more advantageous to reverse the field connections of shunt motors, since the controls have to handle much less current, especially on large motors, than do armature-circuit contactors. An AC motor is reversed by reversing the connections of one leg on three-phase power or by reversing the leads on single phase.

## ROLLER BEARING

A special bearing system with cylindrical rollers capable of handling belted applications, too large for standard ball bearings.

## ROTATING MAGNETIC FIELD

The force created by the stator once power is applied to it that causes the rotor to turn.

## ROTOR

The rotating member of an induction motor made up of stacked laminations. A shaft running through the center and a squirrel cage made in most cases of aluminum which holds the laminations together and act as a conductor for the induced magnetic field. The squirrel cage is made by casting molten aluminum into the slots cut into each lamination.

## S

## SCREENS

Are protection which can be placed over openings in the fan cover on a fan-cooled motor or ventilation openings of a protected motor to help keep out large particles and/or animals, but not block ventilation.

## SECONDARY WINDING

Winding which is not connected to the power source, but which carries current induced in it through its magnetic linkage with the primary winding.

## SERIES DC MOTORS

Where high starting torques are required for a DC motor, the series motor is used. The load must be solidly connected to the motor and never decrease to zero to prevent excessive motor speeds. The load must tolerate wide speed variations from full load to light load.

Typical areas of application are industrial trucks, hoists, cranes, and traction duty.

## SERVICE FACTOR

1. When used on a motor nameplate, a number which indicates how much above the nameplate rating a motor can be loaded without causing serious degradation, (i.e., a 1.15 S-F can produce 15% greater torque than the 1.0 S-F rating of the same motor).

2. When used in applying motors or gearmotors, a figure of merit which is used to "adjust" measured loads in an attempt to compensate for conditions which are difficult to measure or define. Typically, measured loads are multiplied by service factors (experience factors) and the result in an "equivalent required torque" rating of a motor or gearmotor.

## SHORT-CIRCUIT

A defect in a winding which causes part of the normal electrical circuit to be bypassed. This frequently results in reducing the resistance or impedance to such an extent as to cause overheating of the winding, and subsequent burnout.

## SHAFT

The rotating member of the motor which protrudes past the bearings for attachment to the driven apparatus.

## SHUNT WOUND DC MOTORS

Integral-horsepower shunt motors, are used where the primary load requirements are for minimum speed variation from full-load to no-load and/or constant horsepower over an adjustable speed range at constant potential. Shunt motors are suitable for average starting torque loads.

Typical applications include individual drives for machine tools, such as drills and lathes, and centrifugal fans and blowers which are regulated by means of the discharge opening.

## SKEW

Arrangement of laminations on a rotor or armature to provide a slight angular pattern of their slots with respect to the shaft axis. This pattern helps to eliminate low speed cogging effects in an armature and minimize induced vibration in a rotor as well as reduce associated noise. Also can help to increase starting torque.

## SLEEVE BEARINGS

A type of bearing with no rolling elements, where the motor shaft rides on a film of oil.

## SLIP

The difference between the speed of the rotating magnetic field (which is always synchronous) and the rotor in a non-synchronous induction motor is known as slip and is expressed as a percentage of a synchronous speed. Slip generally increases with an increase in torque.

## SPACE HEATER

Small resistance heater units mounted in a motor, that are energized, during motor shutdown, to prevent condensation of moisture on the motor windings.

## SPECIAL PURPOSE MOTOR

Motor with special operating characteristics or special mechanical construction, or both, designed for a particular application and not falling within the definition of a general purpose or definite purpose motor.

## SPLASH-PROOF MOTOR

An open motor in which the ventilating openings are so constructed that drops of liquid or solid particles falling on it or coming toward it in a straight line at any angle not greater than 100 degrees from the vertical, cannot enter either directly or by striking and running along a surface of the motor.

## SPLIT-PHASE START

Motor which employs a main winding and an auxiliary winding, which is called the starting winding. The windings are unlike and thereby "split" the single phase of the power supply by causing a phase displacement between the currents of the two windings thus producing a rotating field. After the motor has attained approximately 75% of rated speed, the starting winding is automatically disconnected by means of a centrifugal switch or by a relay. The motor then continues to run on a single oscillating field which, in conjunction with the rotation of the rotor, results in a rotating field effect. Since there is no rotating field, after the starting winding is de-energized, the rotation cannot be changed until the motor has come to rest or at least slowed down to the speed at which the automatic switch closes. Special starting switches are available as well as special reversing switches which have a means for shunting the open contacts of the automatic switch while the motor is running and thus permits the split phase motor to be reversed while rotating. This type of starting is found typically on single phase fractional motors.

## SPEED

The speed of the motor refers to the RPMs (revolutions per minute) of the shaft. For a three phase AC motor the synchronous speed =

120 x frequency
(frequency is measured in Hertz or cycles per second)
--------------------------------------
# of poles cycles per second

The number of poles are a function of design.

## STABILIZED SHUNT-WOUND MOTOR

A stabilized shunt-wound motor is a direct-current motor in which the shunt field circuit is connected either in parallel with the armature circuit or to a separate source of excitation voltage and which also has a light series winding added to prevent a rise in speed or to obtain a slight reduction in speed with increase in load.

## STANDARDS ORGANIZATIONS

ABS - American Bureau of Shipping
ANSI - American National Standards Institute
API - American Petroleum Institute
BASEEFA - British Approval Service for Electrical Equipment in Flammable Atmospheres
BISSC - Baking Industry Standards Committee
CE - Compliance to European Standards
CSA - Canadian Standards Association
EPACT - 1997 U.S. Energy Policy Act
IEC - International Electrotechnical Commission
IEEE - Institute of Electrical and Electronics Engineers
ISO - International Standards organization
MIL - Military Specifications
MSHA - U.S. Mining, Safety, Health Administration
NAFTA - North American Free Trade Agreement
NEC - National Electric Code
NEMA - National Electrical Manufacturers Association
UL - Underwriter's Laboratories
UR - Underwriter's Laboratories Recognized
USDA - U.S. Department of Agriculture
USCG - U.S. Coast Guard

## STARTING CURRENT

Amount of current drawn at the instant a motor is energized - in most cases much higher than that required for running. Same as locked rotor current.

## STARTING TORQUE

The torque or twisting force delivered by a motor at the instant it is energized. Starting torque is often higher than rated running or full load torque.

## STATOR

That part of an AC induction motor's magnetic structure which does not rotate. It usually contains the primary winding. The stator is made up of laminations with a large hole in the center in which the rotor can turn; there are slots in the stator in which the windings for the coils are inserted.

## STRESS CONES

A physical protection placed over the external connections point on medium- and high-voltage motor leads. Stress cones are used to avoid di-electric breakdown of motor leads in the vicinity of the external connection. Stress cones generally require an oversized conduit box on large motors.

## SUFFIXES TO NEMA FRAMES:

Letter suffixes sometimes follow the NEMA frame size. Some of these suffixes, according to NEMA standards, have the following meanings

### FRACTIONAL HORSEPOWER MOTORS

| | |
|---|---|
| C | Face mounting |
| G | Gasoline pump motor |
| H | Indicates a frame having a larger "F" dimension |
| J | Jet pump motor |
| Y | Special mounting dimensions (see manufacturer) |
| Z | All mounting dimensions are standard except the shaft extension |

### INTEGRAL HORSEPOWER MOTORS

| | |
|---|---|
| A | DC motor or generator |
| C | Face mounting on drive end |
| S | Flange mounting on drive end |
| P | Vertical hollow and solid shaft motors with P-Base flange |
| HP | Vertical solid shaft motors with P-Base flange (normal thrust) |
| JM | Close-coupled pump motor with C-Face mounting and special shaft extensions. |
| JP | Close-coupled pump motor with C-Face mounting and special long shaft extension |
| LP | Vertical solid shaft motors with P-Base flange (medium thrust) |
| S | Standard short shaft for direct connection |
| T | Standardized shaft - "T" frame |
| V | Vertical mounting |
| Y | Special mounting dimensions |
| Z | All mounting dimensions standard except shaft extension |

## SURGE PROTECTION

A capacitor device usually mounted in the conduit box to flatten the voltage surges that may occur as a result of lighting or a power supply surge (short-period peak). These surges could result in more than twice the rated voltage going to the windings and in turn cause winding damage.

## SYNCHRONOUS MOTOR

A motor which operates at a constant speed up to full load. The rotor speed is equal to the speed of the rotating magnetic field of the stator; there is no slip. There are two (2) major types reluctance and permanent magnet on synchronous motors. A synchronous motor is often used where the exact speed of a motor must be maintained.

## SYNCHRONOUS SPEED

The speed of the rotating magnetic field set up by the stator winding of an induction motor. In a synchronous motor the rotor locks into step with the rotating magnetic field, and the motor is said to run at synchronous speed. Approximately the speed of the motor with no load on it.

This is equal to

$$\frac{120 \times \text{Frequency} = \text{RPM (Revolutions per minute)}}{\text{No. Poles}}$$

# T

## "T" FRAME

Current NEMA designation identifying AC induction motor frames. (NEMA has dimension tables which offer standard frame measurements). Replaced the previous standard "U" frame in 1965.

## TACHOMETER

A small generator normally used as a rotational speed sensing device. Tachometers are typically attached to the output shaft of DC or AC inverter motors requiring close speed regulation. The tachometer feeds its signal to a control which adjusts its output to the DC motor or AC inverter motors accordingly (called "closed loop feedback" control).

## TEMPERATURE

Has direct bearing on the life of a given motor and when considering life expectancy, the following application considerations that affect the motor's operating temperature, should be taken into account

1. Bearing
2. Lubricants
3. Duty Cycle
4. Radial Loading
5. Axial Loading
6. Mounting
7. Enclosure
8. Ambient Temperature
9. Ventilation

As a general rule of thumb, each 10ƒC increase in total temperature over the maximum permissible to the motor insulation system halves its life. Bearing or gear lubricant life is halved for every 25ƒF (approx. 14ƒC) increase in temperature. Heat eventually causes deterioration of most lubricants and seals leading to leakage and increased friction.

## "T" (TEMPERATURE CODES)

See N.E.C. Temperature Codes

## TEMPERATURE RISE

Some of the electrical energy losses inherent in motors are converted to heat causing some of the motor parts to heat up when the motor is running. The heated parts are at a higher temperature than the air surrounding them thereby causing a rise above room (ambient) temperature.

It is important to match the proper motor and insulation system (NEMA temp. codes) to the appropriate ambient temperature. If a motor has been built with greater than 1.0 service factor then it can run at a temperature somewhat higher than the motor's rated operating temperature. In all cases, the actual insulation thermal capability usually is higher than the motor's operating temperature to allow for any excessive heat areas. This is called hot spot allowance. (See Insulation Systems for NEMA standard temperature codes.) Each temperature code has an associated temperature rise which when added to the ambient and hot spot should not exceed the temperature handing of the insulation system.

## TEMPERATURE TESTS

Tests conducted to determine the temperature rise of certain parts of a motor above the ambient temperature, when operating under specific conditions.

## TESTS

A variety of tests are conducted to ensure motor performance, efficiency, and manufacturing integrity:

### COMPLETE

A complete test is a test which meets the requirements of IEEE-112-1978. It includes the tests conducted in a Routine Test as well as. full-load heat run; no-load current and watts' determination of torques; efficiencies at 125, 100, 75, 50 and 25 percent of full load; power factor at 125, 100, 75, 50, and 25 percent of full load.

### NOISE

A test performed to verify the motor sound level, conducted in accordance with IEEE-85. The tests are performed under no-load conditions in sound room.

### ROUTINE

A routine test is a basic test done in the factory to the requirements of NEMA MG1, paragraph 12.51 and IEEE-112-1978 and includes the following measurements: no load current/watts; winding resistance; and high potential test.

### WITNESS

A witness test is a test performed with a customer representative present.

## THERMAL PROTECTOR (INHERENT)

An inherent overheating protective device which is responsive to motor temperature and which, when properly applied to a motor, protects the motor against dangerous overheating due to overload or failure to start. This protection is available with either manual or automatic reset.

## THERMISTOR-THERMALLY SENSITIVE RESISTOR

A semiconductor used to measure temperature; can be attached to an alarm or meter to detect motor overheating.

## THERMOCOUPLE-THERMAL DETECTION DEVICE

A temperature detecting device made of two dissimilar metals which generate a voltage as a function of temperature. Thermocouples can be attached to a meter or alarm to detect overheating of motor windings or bearings.

## THERMOSTAT

Units applied directly to the motor's windings which senses winding temperature and may automatically break the circuit in an overheating situation.

## TORQUE

Turning force delivered by a motor or gearmotor shaft, usually expressed in lbs. ft derived by completing H.P. x 5250/RPM = full load torque.

## TOTALLY-ENCLOSED ENCLOSURE

A motor enclosure which prevents free exchange of air between the inside and the outside of the enclosure but is not airtight. Different methods of cooling can be used with this enclosure.

## TOTALLY-ENCLOSED AIR-TO-AIR-COOLED MACHINE

A totally enclosed machine cooled by circulating internal air through a heat exchanger which, in turn, is cooled by circulating external air. Provided with an air-to-air heat exchanger for cooling ventilating air and fan or fans integral with rotor shaft or separate, for circulating external air.

## TOTALLY-ENCLOSED FAN-COOLED ENCLOSURE

Provides for exterior cooling by means of a fan(s) integral with the machine, but external to the enclosed parts.

## TOTALLY-ENCLOSED NON-VENTILATED ENCLOSURE:

Has no provisions for external cooling to the enclosing parts. The motor is cooled by heat radiation from the exterior surfaces to the surrounding atmosphere.

## TOTALLY-ENCLOSED PIPE VENTILATED MACHINE

A totally-enclosed machine except for openings so arranged that inlet and outlet ducts or pipes may be connected to them for the admission and discharge of ventilating air. Air may be circulated by means integral with the machine or by means external to and not a part of the machine. In latter case, these machines shall be known as separately-forced-ventilated machines.

## TOTALLY-ENCLOSED WATER AIR-COOLED MACHINE

A totally-enclosed machine cooled by circulating air which, in turn, is cooled by circulating water. Provided with water-cooled heat exchanger for cooling ventilating air and fan or fans, integral with rotor shaft or separate, for circulating ventilating air.

## TRANSFORMER

A device which converts electrical power (alternating current) to electrical power of a different voltage. In this device both primary and secondary windings are usually stationary, and are wound on a common magnetic core.

## THRUST BEARINGS

Special bearings used to handle higher than normal axial forces exerted on the shaft of the motor as is the case with some fan or pump blade mountings.

## TUBE COOLED

A motor in which heat is dissipated by air-to-air heat exchange.

## U

### "U" FRAME

A previously used NEMA designation indicating frame size and dimension (prior to 1965 the standard frame sizes per horsepower rating).

### U.L. (UNDERWRITER'S LABORATORY)

An independent testing organization which examines and tests devices, systems and materials with particular reference to life, fire and casualty hazards. It develops standards for motor and control for hazardous locations through cooperation with manufacturers. U.L. has standards and tests for explosion-proof and dust ignition proof motors which must be met and passed before application of the U.L. label.

## V

### VACUUM DEGASSED BEARINGS

Vacuum degassing is a process used in the purifying of steel for ball bearings assuring a very dense and consistent bearing surface. This results in a longer lasting superior bearing. All Reliance Electric ball bearings are vacuum degassed bearings.

### VARIABLE TORQUE

A multi-speed motor used on loads whose torque requirements vary with speed as in some centrifugal pumps and blowers. The HP varies as the square of the speed.

### VERTICAL MOTOR

A motor being mounted vertically (shaft up or down) as in many pump applications.

### VERTICAL "P" BASE MOTOR

A vertical motor with a special mounting face conforming to NEMA's "P" design and with a ring groove on the shaft.

### VOLTAGE

The force that causes a current to flow in an electrical circuit. Analogous to pressure in hydraulics, voltage is often referred to as electrical pressure. The voltage of a motor is usually determined by the supply to which it is being attached. NEMA requires that the motor be able to carry their rated horsepower at nameplate voltage plus or minus 10% although not necessarily at the rated temperature rise.

### VOLTAGE DROP

Loss encountered across a circuit impedance from power source to applicable point (motor) caused by the resistance in conductor. Voltage drop across a resistor takes the form of heat released into the air at the point of resistance.

## W

### WK$^2$ (MOMENT OF INERTIA)

The moment of inertia is expressed as Wk$^2$ or WR$^2$ in terms of pound-feet squared. It is the product of the weight of the object in pounds and the square of the radius of gyration in feet.

If the application is such that the motor is driving through a pulley or gear so that the driven equipment is operating at a higher or lower speed than the motor, it is necessary to calculate the inertia "reflected to the motor shaft," that is, an equivalent Wk$^2$(reflected to motor shaft) = Wk$^2$ based on the rpm of the motor.

$$\text{Wk}^2 \text{ (reflected to motor shaft) } = \frac{\text{Wk}^2 \text{ (driven equipment) x (driven equipment rpm)}^2}{\text{(motor rpm)}^2}$$

### WATT

The amount of power required to maintain a current of one ampere at a pressure of one volt. Most motors are rated in Kwatt equal to 1,000 watts. One horsepower is equal to 746 watts.

### WEATHER-PROTECTED MACHINE

Type I (WPI) weather-protected machine is an open machine with its ventilating passages so constructed as to minimize the entrance of rain, snow and airborne particles to the electric parts and having its ventilating openings so constructed as to prevent the passage of a cylindrical rod 3/4 inch in diameter.

### WEATHER-PROTECTED MACHINE

Type II (WPII) shall have, in addition to the enclosure defined for a Type 1 weather-protected machine, its ventilating passages at both intake and discharge so arranged that high velocity air and airborne particles blown into the machine by storms or high winds can be discharged without entering the internal ventilating passages leading directly to the electric parts of the machine itself. The normal path of the ventilating air which enters the electric parts of the machines shall be so arranged by baffling or separate housing as to provide at least three abrupt changes in direction, none of which shall be less than 90ƒ . In addition, an area of low velocity not exceeding 600 feet per minute shall be provided in the intake air path to minimize the possibility of moisture or dirt being carried into the electric parts of the machine.

### WOUND ROTOR INDUCTION MOTOR

A wound rotor induction motor is an induction motor in which the secondary circuit consists of polyphase winding or coils whose terminals are either short circuited or closed through suitable circuits. A wound rotor motor is sometimes used when high breakdown torque and a soft start or variable speed are required.

### WYE-DELTA STARTING

A method of starting a motor at rated voltage but drawing locked rotor current and producing reduced stocked rotor torque but it provides lower starting torque than a straight delta connection. Once the load and motor have been started the wiring will switch from the wye connection to a delta connection in which mode it must run and deliver full torque.

# BUYER'S GUIDE

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